



PHD

An Investigation into Integration of Renewable Energy Source for Electricity Generation: A Case Study of Cyprus

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An investigation into integration of renewable energy source for electricity generation
A case study of Cyprus

Davut Solyali

A thesis submitted for degree of Doctor of Philosophy

Department of Electronic & Electrical Engineering

University of Bath

February 2013

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Abstract

Cyprus is an island in the Mediterranean Sea. It has an isolated electricity grid and energy system which is fully reliant on imported fossil fuels. Burning fossil fuels for electricity generation has a negative impact on the environment due to the greenhouse gas emissions and importing the fuels places a huge burden on the economy of the country and a risk in terms of the electricity supply security of the island.

One way to reduce dependency on imported fuels is to implement renewable energy solutions in the island. There are many studies assessing the availability of renewable energy sources, evaluating future electricity demand and investigating methods of demand reduction in Cyprus but there are a very limited number of studies specifically produced for Cyprus that address the integration and cost of renewable energy sources and explore their effects on the grid system.

This thesis illustrates the big picture of Cyprus in terms of availability of exploitable renewable energy sources, current electricity generation and electricity demand characteristics. In order to address the grid code barrier, the grid codes of developed European countries are investigated. From this research, amendments to the current grid are produced. These additional mandatory codes will form the infrastructure for renewable energy projects and bring knowledge to the current system operator from other experienced countries.

In addition renewable energy technologies worldwide are investigated in terms of output capacity, energy pricing, investment, and operation costs. Pricing and cost information is applied to the case of Cyprus. By further optimizing the technologies appropriately to Cyprus conditions, current and future cost analysis is produced. By producing reliable data on the cost and performance of renewable energy technologies the significant barrier to the uptake of these technologies is lowered. This will enable governments and financial bodies to arrive at an accurate assessment of which renewable energy technologies are the most appropriate for their particular circumstances.

List of Abbreviations

Automatic generation control (AGC)

Automatic voltage regulators (AVRS)

Build Margin (BM)

Balance of system (BOS)

The clean development mechanism (CDM)

Certified emission reduction (CER)

Cyprus Energy Regulatory Authority (CERA)

Combined margin emission factor (CM)

Conference of the Parties serving as the meeting of the Parties to the Kyoto Protocol (CMP)

Concentrating solar power (CSP)

Doubly fed induction generator (DFIG)

Rotating distributed generation (DG)

Distributed generation with high penetration of renewable energy sources (DISPOWER)

Debt-service coverage ratio (DSCR)

The Electricity Authority of Cyprus (EAC)

European Environment Agency (EEA)

European network of transmission system operators for electricity (ENTSO-E)

Electric Power Research Institute (EPRI)

Flexible AC Transmission Systems (FACTS)

Fault Ride through (FRT)

Green house gas (GHG)

High voltage direct current (HVDC)

Internal rate of return (IRR)

Electricity Authority of Northern Cyprus (KIBTEK)

Load duration curve (LDC)

Linear Fresnel Reflector (LFR)

The loss of energy expectation (LOEE)

The loss of load expectation (LOLE)

The loss of load probability (LOLP)

Low Voltage Ride through (LVRT)

Operating margin (OM)

The point of common connection (PCC)

The power purchase agreement or bid (PPA)

Photovoltaic (PV)

PV power systems (PVPS)

Renewable Energy Services (RES)

Voluntary regional group isolated systems (RG IS)

Republic of Cyprus (ROC)

System Advisor Model (SAM)

Short circuit ratio (SCR)

The Solar Electric Generating Systems (SEGS)

Solar renewable energy source (S-RES)

The Turkish Republic of Northern Cyprus (TRNC)

Cyprus Transmission System Operator (TSO)

Europe's Transmission System Operators (TSOs)

Transmission and distribution losses (TxD LOSSES)

United Nations Framework Convention on Climate Change (UNFCCC)

Wind energy conversion system (WECS)

Wind Energy Resource Analysis (WERA)

Zero Voltage Ride through (ZVRT)

CHAPTER 1

INTRODUCTION

This chapter briefly describes Cyprus's challenge, research motivation, objectives, and contribution of this work. It also provides an overview of the thesis.

1. Introduction

1.1. The Challenge for Cyprus

Cyprus is a Mediterranean island. For centuries, many powerful empires and leading civilisations conquered, ruled, and inhabited the island. Therefore, it has a very rich historical heritage including monuments related to the culture of those who lived in the island. The unspoiled beauty, sunny weather, and rich historic presentation of the island attract many tourists from all over the world. One of the main sources of the island's income is hence the tourism sector. The island, because of its attractiveness and touristic values, is called the 'pearl' of the Mediterranean Sea.

Although the world recognises the island as a country, the reality is different. After the Greek-Turkish war on the island, the island was divided and there have been two de-facto areas since 1974. The southern area has become part of the European Union (EU) in 2004. The northern area, on the other hand, remained unrecognized by the rest of the world except Turkey.

Despite many peace meetings; face-to-face talks; peace plans suggested by the United Nations, no major breakthrough could have been achieved to reach a settlement to the long-standing problem of the divided island. Throughout the years, the EU recognised the southern area that has access to EU's economical aids and attracted tourism from all over the world. The embargoed northern area on the hand is forced to seek help from Turkey and become more and more dependent on it.

Although the two areas share the same folklore, historical heritage, weather, land, and resources, the gap separating the divided island has been steadily widening. One reality is that two areas share the same earth resources and are isolated from rest of the world in terms of electric supply. Concerning energy infrastructure, both areas are able to share electrical supply, but they choose not to unless there is a major event (i.e. loss of major power stations or blackouts requiring re-energising of the entire system). Both areas' total energy demands are met through the consumption of the imported oil products.

Increasing population, rising life standards, and rapidly growing tourism and industry sectors have led to increased energy demands. Being an isolated energy system, this increase in demand is causing a high degree of dependence on imported oil as well as a high burden on the economy of the country. Owing to the increasing cost of energy supply, limited oil storage capacity, and the need for environmental preservation (i.e. reduction of green house gas emissions, conservation of the natural and visual beauty of the island), Cyprus is looking into effective exploitation of renewable sources. The two areas, although politically and socially separated from each other, share the same goals in terms of the needs of energy supply, quality, and security.

One of the ways of reducing the dependency on imported fuels is to implement renewable energy solutions in the island. In Southern Cyprus, a part of the EU, a target gross electricity generation of 13% is set to be supplied by renewable energy sources by the year 2020 as per the European Climate Change Program; similar targets are set in the North.

Key players in renewable energy, especially concerning investment, consist of both existing clients, i.e. conventional power generators and system operators, and future investors, i.e. financiers. Financiers seek deeper understanding of and give priority to the underlying drivers for the renewable energy (RE) strategy by the policy-makers at a national level with respect to visibility in market development and growth in the near and medium terms. Hence, policy and regulation are central to investment conditions. The majority of governments do not have a national regime in place despite the developments and targets set i.e. those set by EU Directives.

Access to the market, alignment of or embedding renewables within utility or energy policy more broadly, government strategies on both technology development and deployment, and importantly medium-term visibility on transmission, and interconnection planning are all core requirements deemed by investors.

Subsidised conventional fuel, together with the proportionately higher up-front cost of renewable energy, are also deemed as important issues in the region for policy development and project economics.

The island has a cumulative supply capacity of approximately 1.3 GW and population of approximately 1.2 million, equivalent to 1/60th of the United Kingdom's electricity supply capacity and population. Owing to the electricity system's size on the island, there has been no implementation or plans for implementing renewable energy sources for electricity generation. Because of this fact, the grid code, which is used by the system operators to manage and operate the current system, is not designed to accommodate the integration of the renewable energy sources.

Furthermore, any utility-scale renewable energy project would be as the first of its kind owing to the lack of experience in terms of financing, implementation, and operation of these systems in the island. Because of these perceived and associated risks, a barrier is created against incorporating renewable energy technologies in Cyprus.

Many studies have assessed the availability of renewable energy sources and evaluated future electricity demands and methods of demand reduction in Cyprus. However, the numbers of studies, specifically concerning Cyprus, that address the integration and cost of renewable energy sources and explore their effects to the grid system, are scarce. This thesis aims to fill this gap.

1.2. Objectives

The main objective of this research is to break the barriers created against incorporating renewable energy technologies in Cyprus.

In order to achieve this goal the following objectives are aimed to be:

- 1-Establishing the drivers of the current electricity demand of Cyprus and quantifying its behaviour
- 2-Investigating and quantifying the availability of renewable energy sources of Cyprus
- 3-Investigating the technical and policy changes introduced to electricity system of the developed countries following use of renewable energy sources
- 4-Proposing grid code change for Cyprus to welcome RES connections and operations by using and applying the findings of the research of the developed countries
- 5- Comparing different RES technologies in terms of grid operations and effects on the electricity demand curve
- 6- Providing an economic review of the cost of electricity of RES technologies with current and future scenarios of cost of electricity and with different sensitivities of DSCR values.
- 7- Providing a discussion and inspiration in the terms of future work and research topics to be pursued to expand on this research.

1.3. Contribution

This thesis aims to determine the availability of exploitable renewable energy sources, current electricity generation, and electricity demand characteristics in Cyprus. Cyprus's energy demand is growing and the necessity to secure and supply quality electricity is becoming highly onerous. The burden on the economy in terms of energy has to be shifted from imported fuel to sustainable and secure resources.

This thesis has established that Cyprus, where the conventional generators have overall average efficiencies of 36%, is one of the highest emission producers in Europe. The domestic electricity demand is one of the largest contributors to the total electricity demand. Moreover, this demand is growing and will continue to grow with the increasing life standards and population. Despite this fact, research has showed that insulation measures, to reduce or minimise the use of energy in domestic buildings, are scarce. Research has also indicated that the potential of energy savings by implementing such measures can be as much as 19% in heating and 46% in cooling. When these figures are applied to overall demand; the savings can be as much as 15% for cooling and 6% for heating. However, even though these savings can be implemented by using insulation measures, the future estimated electricity demand growth will range from 34% to 50% by the year 2020.

Therefore, this thesis draws attention to use of renewable resources. Within the thesis tidal, biomass, wind, and solar resources will be investigated and quantified. The outcome of the research regarding these resources indicated that solar and wind energy sources are the two most exploitable natural resources. Using the data collated from preceding related studies as well as many years of metered data, the wind and solar energy potential of the island is presented. Wind technologies yielded to load factors of between 8% and 23%, whereas solar technologies yielded between 17% and 28%. Therefore, the presented data indicated that wind and solar energy resources are, indeed, exploitable resources for energy production for the island.

Despite the results from this analysis, the current state of use of renewable energy sources in the island in the terms of producing electricity is very limited. In a bid to exploit the abundantly available solar energy, Cyprus has been using solar thermal heaters extensively. Cyprus has more than double the number of installed solar thermal collectors and produces twice the energy using these systems than Austria. However, there is no large-scale (>1 MW) solar-to-electricity project linked to the electricity system. Since 2004, 25 applications for wind parks with a total capacity of approximately 515 MW have been made by the concerned authorities of southern Cyprus. However, today there is only one operational site, Orites, with installed capacity of 144 MW.

Clearly, there are barriers preventing the uptake of implementation of the renewable energy technologies. The thesis establishes that the current level of investment in renewable resources is affected by various barriers. These barriers can be summarised under two main titles called policy/regulations and technical barriers.

Policy or regulation barriers can prevent financiers or investors from investing in the projects and are central to investment conditions. However, the majority of governments do not have a national regime in place, despite the developments achieved and targets set i.e. by EU Directives. Access to the market, alignment or embedding renewables within utility or energy policy more broadly, government strategies on both technology development and deployment, and importantly medium-term visibility on transmission, and interconnection planning are all core requirements deemed important by investors. Lack of policy and regulations and experience in technology have led to high investment risks. Furthermore, large scale projects end up being ‘the first of their kind’ in Cyprus at present. Although the electricity authorities are approving various large scale projects, the final regulations regarding town planning/building laws for these kinds of projects are not enacted and this adds to the barriers. Such a large scale project will be the very first commercially operated project and staffing and knowledge of infrastructure (construction, operations, and maintenance) will start from scratch leading to increased training costs. In addition, the projects will introduce technology from abroad. All material and even crane facilities for erection of the turbines will have to be imported, leading to high costs, placing an extra burden on the financiers and diminishing the interest of the investors.

On the other hand, in the terms of technical barriers, current electricity production in Cyprus is operated and controlled by the governmental electricity authorities. A new large scale project will be the very first to intervene and interact with the conventional generation and current demand profile. Considering that Cyprus has been set with very ambitious targets regarding the level of penetration of renewable power generation, the implementation of multi-megawatt RES generation may cause some problems in system operations.

The penetration of renewable energies in the power grids has been increasing in the last couple of years because of successful implementation of regulations by the European countries. Therefore, the experience from these European countries can be used as guidelines in infrastructure to amend the current grid code which has no reference to RES technologies and their effects. With the new extended grid code; connection of RES technologies will be well defined and their negative effects will be diminished; in fact, depending on grid requirements, their impact may prove to be positive.

This thesis establishes that the amendments in the grid code for Cyprus can be summarised under the main titles of ‘active power control’, ‘fault ride through capability’, ‘automatic frequency response’, ‘reactive power control’ and ‘communications and notifications’.

In the terms of implementing and investing of renewable technologies, the absence of accurate and reliable data regarding the cost and performance of renewable power generation technologies is therefore another significant barrier to the uptake of these technologies.

Without access to reliable information on the relative costs and benefits of renewable energy technologies it is difficult, if not impossible, for the governmental authorities, investors, or financiers to arrive at an accurate assessment of which renewable energy technologies are the most appropriate in terms of finance, technical, operations, and duration.

In order to create and run a valid analysis, renewable energy technology will be evaluated in comparison with a conventional technology, so that the analyses of all analyzed technologies is based on comparable characterisations. Similarly, the analysis will be conducted on relevant and consistent macroeconomic and microeconomic bases.

The levelized cost of energy (LCOE) allows alternative technologies to be compared when different scales of operation or different investment and operating time periods or both exist. Hence, in this study, mainly solar and wind technologies will be compared against the conventional energy systems of Northern and Southern Cyprus based on the LCOEs of their sold or to be sold electrical energy.

Sensitivity studies were conducted to define optimal values for both loan term and PPA escalation rate in order to minimise the LCOE. This sensitivity study studied PPA escalation rate from 1% to 3% in 0.5% steps and loan term from 10 years to 30 years in 5-year steps. Results of the sensitivity study for defining loan term against escalation rate indicated that the choice of loan term of 30 years with PPA escalation rate of 1.5% would have the lowest LCOE. Hence, these values were chosen to be used in this study.

In order to be able demonstrate the results for the current electricity system, the trend of electricity price of the KIBTEK, since 1995 until today, has been extrapolated throughout the years of 2013 to 2042. Three scenarios, ‘Scenario – Parabolic’, representing the most probable and highest rise in the cost of electricity; ‘Scenario – Linear Medium’; and ‘Scenario – Linear Low’, both representing slow rise in the cost of electricity, are illustrated.

The Debt service coverage ratio (DSCR) is the ratio of operating income to costs in a given year. Present and future projects with different DSCR ratios are studied against three different trends of present and future cost of electricity of conventional generators. Using these three scenarios, four different cases for each RES technology are compared to each other and to the cost of electricity of the conventional generation. The four cases are 2013 with DSCR 1.1, 2013 with DSCR 1.5, 2020 with DSCR 1.1, and 2020 with DSCR 1.5. The cases concerning year 2013 are representing the projects with present time costs.

The cases concerning 2020 are based on the future costs estimated by this study by surveying published sources.

The results from the first scenario, 2013 with DSCR at 1.1, demonstrated that wind power has the lowest cost of approximately 25 cents/kWh compared to those of a CSP tower at 30 cents/kWh, CSP trough plant at 34 cents/kWh, and PV plant at 43 cents/kWh. This significant difference of cost is applied to the cost of electricity and to the years taken to at least match the cost of electricity of conventional power plant electricity of KIBTEK. In this sense, wind power takes almost 25 years to match KIBTEK's cost of electricity. On the other hand, solar technologies fail to reach a price as low as that of the KIBTEK's cost of electricity within their operational lifetime of 30 years.

The results from the second scenario, 2020 with DSCR at 1.1, showed that wind power has the lowest cost of approximately 14.7 cents/kWh compared to that of a CSP tower at 23.3 cents/kWh, CSP trough plant at 33.96 cents/kWh, and PV plant at 27.46 cents/kWh. The cost of Wind power is almost as low as the 'Scenario – Linear Low' cost of electricity of conventional generators. It is almost \$0.05/kWh lower than the 'Scenario – Parabolic' cost. CSP Tower manages to match the cost of electricity of conventional generators after 8 years and solar technologies after 17 years of operation.

The third scenario, 2013 with DSCR at 1.5, showed that wind power has the lowest cost of approximately 20.6 cents/kWh compared to that of a CSP tower at 24.31 cents/kWh, CSP trough plant at 27.6 cents/kWh, and PV plant at 33.8 cents/kWh. It will take 14 years for wind technology to match the cost of electricity of conventional generators. The CSP tower manages to match the cost of electricity of conventional generators after 23 years. On the other hand, the remaining solar technologies fail to reach a price as low as that of the KIBTEK's cost of electricity within the operational lifetime of 30 years.

For the fourth scenario, 2020 with DSCR at 1.5, showed that wind power has the lowest cost of approximately 10.95 cents/kWh compared to that of a CSP tower at 18.68 cents/kWh, CSP trough plant at 22.28 cents/kWh, and PV plant at 21.99 cents/kWh. It will take approximately 5.5 years for the costs of PV and CSP trough technologies to match the cost of electricity of conventional generators. The cost of wind technologies on the other hand is almost \$0.05/kWh lower than the 'Scenario - Linear Low' costs of KIBTEK, whereas that of the CSP-tower is lower than 'Scenario- Parabolic' and almost identical to the 'Scenario – Linear Medium' of estimated conventional generators' cost of electricity.

To demonstrate the effect on the demand curve by using RES technologies along with conventional generators, the daily electricity curve with and without the RES contribution needs to be illustrated. For demonstration purposes only, 3 typical days of the year from January, July, and November were chosen.

Electricity demand is affected by variables such as relative humidity, cloudiness, solar radiation, wind speed, electricity price, gross domestic product growth etc. In most electricity systems, the residential sector is one of the main contributors to the load peaks.

The domestic electricity demand significantly increases especially in the summer season, because of the increasing use of air-conditioning (AC) systems, which have drastically changed the thermal comfort needs of urban population in the developed countries. The strong penetration of the AC systems in the market was also quickened by the sudden and rapid reduction of their costs, resulting in an increase in the 'urban heat island' effect. Urban heat island is an area generally a city where is significantly warmer than its surrounding rural areas due to the human activities. This urban heat island and its effect are further discussed later in this thesis at chapter 5.

The balance point temperature is the outdoor air temperature causing building heat gains to be dissipated at a rate that creates a desired indoor air temperature. Any higher or lower temperatures from the balance point temperature would result to a higher electricity demand due to need of cooling or heating. To determine the average balance point temperature of Cyprus, each year's data, from 2000 to 2010, is studied. There have been fluctuations of the balance point temperature of Cyprus throughout these years. Nevertheless, the average balance point temperature throughout these years is observed to be 16.9°C.

Through the relationship between air temperature and electricity demand and the relationship between air temperature and solar irradiation, the indirect relationship between solar irradiation and electricity demand has been identified. Therefore, the predictability of solar radiation and its indirect relationship with the electricity demand enables the system or grid operator to predict the peak demands that cause the solar radiation in the first place.

Based on the fact that electricity demand is linked to air temperature and air temperature is linked to solar radiation, solar energy is one of the best options that can be exploited to provide power to the grid system in matching peak demands in Cyprus.

The highest demand periods are seen during the day, with seasonal demand cycle peaking during summer, which are correlated with the solar generation output. However, it is not immediately obvious how solar or other renewable generation in this case interacts with overall demand profile as the RES generation achieves increasing levels of penetration, especially during non-summer time periods when electricity demand is not driven by air conditioning.

Unlike conventional generators, intermittent sources of electricity cannot respond to the variation in normal consumer demand patterns. Rapid fluctuations in output can impose burdens on generators and limit their use. The ability to integrate fluctuating sources is improving, and it is unclear as to what extent these short-term fluctuations limit the fraction of a system's energy that can be provided by intermittent renewable sources. There is, however, an absolute limit to the economic integration of renewable energy sources such as solar PV or wind, owing to the fundamental mismatch of supply and demand. Only so much RES generation can be integrated into an electrical power system before the supply of energy exceeds the demand. This problem is exacerbated by conventional power systems, which have limited ability to reduce output of base-load generators.

An extensive literature search was conducted to collect the available information on expected problems associated with high penetration levels of grid-connected PV systems. These problems were due to the ramp rates of main line generators, reverse power swings during cloud transients, unacceptable unscheduled tie line flows, frequency control, voltage rise, unacceptable low voltages during false trips and distribution system losses etc. However, none of the literature was specific to Cyprus. Therefore, the exact value of the level of upper limit for PV penetration is not defined. Concerning wind, it is very important to take account its variability accurately in the power system. The factors that cause the variability in wind resources are meteorological conditions, daily/seasonal variations of wind speed (monthly, diurnal), specific site and height, and geographic dispersion of wind plant. Depending on the penetration of a power system with variable wind energy, additional indirect costs arise for maintaining system reliability to supply the varying demand, because wind energy will not be able to meet the demand at its average capacity factor, but the demand will be met at a generally reduced rate, depending on its capacity credit.

In addition, the presence of wind power in a power supply system introduces short-term variability and uncertainty, and therefore requires balancing reserve scheduling and unit commitment. Grid operators need to meet peak demands to certain statistical reliability standards even when wind output falls relative to load. During these periods, which range from minutes to hours, electricity markets need to recruit demand-following units (such as gas, hydro, or storage), which at times of sufficient wind remain idle, so the costs arise essentially for two redundant systems and for inefficient fuel use during frequent ramping.

Thus, wind energy reduces dependence on fuel inputs but does not eliminate the dependence on short-term balancing capacity and long-term reliable load-carrying capacity.

The effect of wind power on the power supply system is critically dependent on the technology mix in the remainder of the system, because the more flexible and load-following the existing technology, the less peak reserves needed. It is also dependent on time characteristics of system procedures (frequency of forecasts etc) and local market rules.

In general, the higher the wind penetration, the higher the variability in the supply system, and the more long-term reserve and short-term balancing capacity has to be committed. The corresponding cost increases are only partly offset by a smoothing out of wind variability when many turbines are dispersed and interconnected over a wide geographical area.

It was observed that wind energy was offsetting the conventional generation throughout the day. The amount of offset depends on the time, day, and the season of the year. PV, on the other hand, starts offsetting the conventional generation from dawn until dusk. The overall impact, the plateau demand, from morning to late afternoon is reduced and troughed. The evening peak remains the same. Compared to PV, CSP plants begin producing electricity after a delay of a couple of hours due the requirements of steam boilers and storage facilities. The CSP trough has a rather short storage capacity and hence shows similar behaviour with the PV. However, CSP tower, because of its size and long storage capacity, is able to offset a large amount of conventional generation starting from morning until late

night and flex its output according to the operator needs. Two different cases of CSP tower were calculated. The case called 'Tower' was a case in which storage capacity is actively used to store and dispatch energy, thereby maximising the instantaneous output when sun is shining. On the other hand, the case called 'Tower 2' illustrated one of the biggest advantages of the CSP storage which is the use of storage to offset the conventional generation by following the demand curve and offsetting the conventional generation to a fixed level.

The levels of generation used in the calculations were determined after series of simulations which determined the lowest levelized cost of energy (LCOE). The further details are explained in chapter 6. The level of PV, trough, tower and wind is 50MW, 50MW, 130MW and 27MW respectively.

The resultant fixed level of conventional generation means that conventional generation can run as base-load units and solar CSP will vary its output with use of its storage capabilities by following the demand curve. Therefore, by fully utilising storage capabilities of such a system, the daily peak demand will cease to exist and be reduced from 200 MW to 107 MW. Moreover, the daily peak demand will be reduced from 152 MW to 51 MW in November and from 192 MW to 52 MW in January. An immediate advantage of this load-profile smoothing is that the operators can make the best use of the base load generators by using fuel oil and avoid using the fast-response diesel generators.

1.3. Thesis Structure

Second chapter is introducing the current state of electricity demand and generation of the island. It provides concise information about geography, climate and demography of the island. Electricity demand and breakdown of the sectors which form this demand is illustrated. Growth of electricity demand and its growth trend is introduced. One of main contributor of the electricity demand is domestic demand. The breakdown of electricity use of a typical house is shown. The effects of use of insulation in housing are explored. Renewable energy technologies that are used in housing are explored. Furthermore, the electricity supply capacity and the generation which forms this capacity are provided.

Third chapter investigates the potential of different renewable energy resources such as wind, solar, biomass and tidal. Due to their availability, the emphasis is given to wind and solar resources and they are explored in depth. Maps and characteristics of these sources are produced. Barriers preventing uptake of renewable energy sources are identified. Operational and ongoing wind farm projects are investigated and explored.

Fourth chapter introduces different technologies for exploiting solar and wind energy. It compares each technology providing insight to their inner workings, pros and cons. It also provides examples with their technical details around the world where these technologies are implemented.

Fifth chapter explores the requirements of integration of renewable energy technologies to the Cyprus's grid system. It starts with looking into solar, air temperature and peak electricity demand of Cyprus. The correlations between these 3 variables are explored and identified. It introduces the requirement of system flexibility and explores the effects of wind's variability on the system operation. It investigates the grid codes of developed European countries and identifies mandatory codes which are to be added to the current grid code.

Sixth chapter provides an economic analysis of implementation of renewable energy technologies. Using the information from the projects all around the world, especially Europe, each technology is investigated. Each technology is then further optimized according to the conditions and resources of Cyprus. Following thousands of simulations, results of the economic analysis is provided.

Seventh chapter summarizes all the findings and results of the whole project and lists the main contributions. Furthermore introduces ideas and cases for further research.

Eighth chapter lists all the references and sources used in this study.

Ninth chapter lists the publications of the author to this date.

CHAPTER 2

PROJECT BACKGROUND

This chapter introduces the current state of art of the island. It provides concise information about geography, climate and demography of the island. Electricity demand, rate of growth of electricity demand is studied. The electricity supply capacity and the generation which forms this capacity are provided.

2. Project Background

2.1. Geography and Demographics of Cyprus

Cyprus is the third biggest island in the Mediterranean Sea. It is located at the latitude and longitude of 35°00 N, 33°00 E and covers 9,251 km² of land. Since 1983, the island is divided into two de-facto states known as the Northern Cyprus and the South Cyprus. The Northern Cyprus is governed by Turkish Cypriots under the Turkish Republic of Northern Cyprus (TRNC) [1]. This area covers 3,355 km² (36% of total) of land [1] and has a population of 294,000 according to the latest census done in December 2011 [2]. The South Cyprus is governed by Greek Cypriots under the Republic of Cyprus (ROC). This state covers 5,458 km² (59% of total) of land [1] has a population of 862,000 according to the latest census done in October 2011 [3]. The remaining 438 km² (5% of total) area is administered as Sovereign Base Areas of the British Overseas Territory of areas called Akrotiri and Dhekelia.

Cyprus has long been a crossing point between Europe, Asia and Africa and still has many traces of successive civilizations such as Roman theatres and villas, Byzantine churches and monasteries, Crusader castles, Ottoman Mosques and pre-historic habitats. The island's main economic activities are tourism, clothing and craft exports and merchant shipping. Traditional crafts include embroidery, pottery and copper work [1]. The figure 1 below is a map picture extracted from Google Maps showing the island of Cyprus to the south of Turkey and North-West of Lebanon in the Mediterranean Sea [4].



Figure 1: The Island of Cyprus at the south of Turkey and North-West of Lebanon [4].

2.2. Climate and housing in Cyprus

All parts of Cyprus enjoy a very sunny climate. In the central plain and eastern lowlands, the average number of hours of bright sunshine for the year has been measured as 75% of the time that the sun is above the horizon. Over the six summer months, there is an average of 11.5 hours of bright sunshine per day whilst in winter this is reduced to 5.5 hours [5]. These periods of sunshine are amongst the longest in the world and the solar intensity is one of the greatest. Solar energy has been heavily exploited in Cyprus for many years, albeit not for bulk electricity generation.

The present house construction method is similar all over Cyprus. The bearing structure of a building, which may be either a large multi-storey building or a single storey one, consists of the foundations, the columns, the beams and slabs. The bearing structures use reinforced concrete [6].

The walls are constructed from hollow bricks, covered with plaster on both sides. External walls have a thickness of about 25 cm and internal walls a thickness of about 15 cm. During recent years there is a trend to use cavity external walls, constructed of two brick walls with a layer of insulation of about 5 cm between. The floors are made of concrete slabs, covered with a layer of sand or screed of about 10 cm in which all plumbing and other services are placed. The floor finishing consists of a layer of mortar covered with tiles, marble, or granite blocks [6].

Flat roofs consist of the slab, usually 150 mm thick, with an additional layer of plaster of 3 cm on the underside, applied when the slab is not fair-faced, i.e. smooth. The roof is usually water-proofed with a thin layer of bitumen and painted a white or aluminium colour on top. Recently, there has been a trend to use an inclined, fair-face slab, with light insulation, covered with a layer of mortar and roof tiles [6].

2.3. Current use of Renewable Energy Systems (RES) in housing of Cyprus

Cyprus is the highest user of solar water heaters in Europe. The European Solar Thermal Industry Federation (ESTIF) ranks Cyprus as the leader in installed solar collectors per capita. With more than 900,000 m² of installed solar collectors, there is the potential to produce almost 700,000 kWh of thermal energy. Cyprus has more than double the number of installed solar thermal collectors than the second most solar water heater user Austria [7].

The typical solar water system can provide all the necessary hot water that a family of four requires during the 4 months, June to September; and saves about 360 kWh of electricity. The pay-back period using cash-flow analysis is estimated to be 5 years. Solar water heating using flat-plate collectors is a mature technology in Cyprus [8].

Cyprus has mean diurnal variations in ambient temperature of 8 °C in winter and 14 °C in summer. Extreme variations of 18–20 °C occur frequently both during winter and summer. Despite these conditions thermal mass of housing has not been used to reduce the overall energy consumption of typical houses [9].

Studies have been carried out for residential buildings in the Mediterranean region and deals with a specific type of house in Cyprus. Such a house represents the rising trend for using central air-conditioning. Inherently it has the greatest potential for energy savings [10]. The framework, within which the profile of the house base-case was outlined, is defined in the respect of traditional Cypriot architecture, response to current housing trends and demands and by considerations of climatic and thermal aspects.

Then the insulation variable was tested on the building's walls, floors and roof. The introduction of insulation on the roof presents a high energy savings. 50mm insulation thickness proved most appropriate to be used to minimizing energy load. The resultant of the studies for the use of 50mm roof insulation showed that there would be as much as 19% saving in heating energy and as much as 46% in cooling energy [9].

Nevertheless, the use of domestic renewable energy sources and thermal insulation is very limited. Beyond the extensive use of solar water heaters, the use of other renewable installations, e.g. photovoltaic panels, is extremely limited. Regarding heat insulation measures, only double glazing, installed in 43.2% of households, is commonly available, while the use of heat insulation on walls, 7.5%, and roofs, 5.5%, is limited [11].

2.4. Current electricity generation and corresponding CO₂ emissions of Cyprus

Electrical energy production in South is operated by Cyprus Transmission System Operator (TSO). The available generation capacity in South Cyprus used to be 1222 MW [12]. However, it has to be noted that an explosion that occurred at the southern coast of Cyprus next to the Vassilikos Power Station on the 11th of July 2011 has caused extensive damages to the power station that was taken out of operation. The Vassilikos Power Station used to supply more than 50% of South Cyprus's electricity needs [15].

In order to remedy the sudden difficulties which have arisen, South Cyprus has temporarily taken some safeguard measures such as [15];

- Mandatory use of all stand-by units (260 units of an estimated capacity of 68MW),
- Temporary closure of all desalination units,
- Voluntary reduction of consumption from all consumers,
- Selective sequential interruption of geographical areas for a period of between 1-2 hours, (interruption of important and sensitive groups of consumers was avoided)
- Voluntary load shedding,
- Priority of supply to certain type of consumers, etc.

The Electricity Authority of Cyprus (EAC) contracted temporary generating units with a total capacity of 165MW for a six month period. These temporary generating units were installed and put in operation since 31st of August 2011 [15].

Furthermore, in order to avoid extensive interruptions of supply, power was purchased through a third party under the “green line trade” collaboration originating from power stations operating in the Northern Cyprus [15]. Green line trade is a mechanism which allows the two de-facto states to do business with each other.

Overall, the available capacity is planned to be increased to 1338 MW in January 2013 and 1598 MW in June 2013 [16].

On the other hand, in the North, electricity production is owned and controlled by the governmental body which is called Electricity Authority of Northern Cyprus (KIBTEK). It has the available generation capacity of 347.5 MW [13].

Figures 2 and 3 show the breakdown of electricity generation in type and their capacity per station in South and Northern Cyprus respectively. It should be noted that these tables exclude any available renewable energy power generation stations as they are excluded from the capacity contributing the available generation capacity. These generators will be further explored in the following chapter.

	EAC / Moni	EAC / Dhekelia	EAC / Vassilikos	
Combined Cycle Plant			330 MW	
Steam Turbine	120 MW	360 MW		
Gas Turbine	150 MW		37.5 MW	
Diesel Engine		100 MW		
Installed Capacity	270 MW	460 MW	367.5 MW	1097.5 MW
Available Capacity	150MW	400 MW	0.0 MW*	917.5 MW

Figure 2: Breakdown of electricity generation in type and capacity per station in South Cyprus [12]. *Due to damages at power station in July 2011.

	KIBTEK / Teknecik	KIBTEK / Dikmen	AKSA / Kalecik	
Steam Turbine	120 MW			
Gas Turbine	50 MW			
Diesel Engine	70 MW	20 MW	87.5 MW	
Installed Capacity	240 MW	20 MW	87.5 MW	347.5 MW
Available Capacity	217 MW	20 MW	87.5 MW	324.5 MW

Figure 3: Breakdown of electricity generation in type and capacity per station in Northern Cyprus [13].

Within the current state of electricity system of Cyprus, steam turbine units have range of efficiencies from 25% to 36%, gas turbines has a range from 18% to 26%, combined cycles and diesel engines between 40% to 45% [16]; averaging to an overall efficiency of power generation 36% since 2006.

The published data of European Environment Agency (EEA) in 2011 regarding the CO₂ generated electricity per kilo-Watt hour in 2009 per member country indicates that Cyprus is one of highest emissions producer with a 0.67 kg per kWh in Europe. The figure 4 shows the data which belongs to the European countries as of 2009 [17].

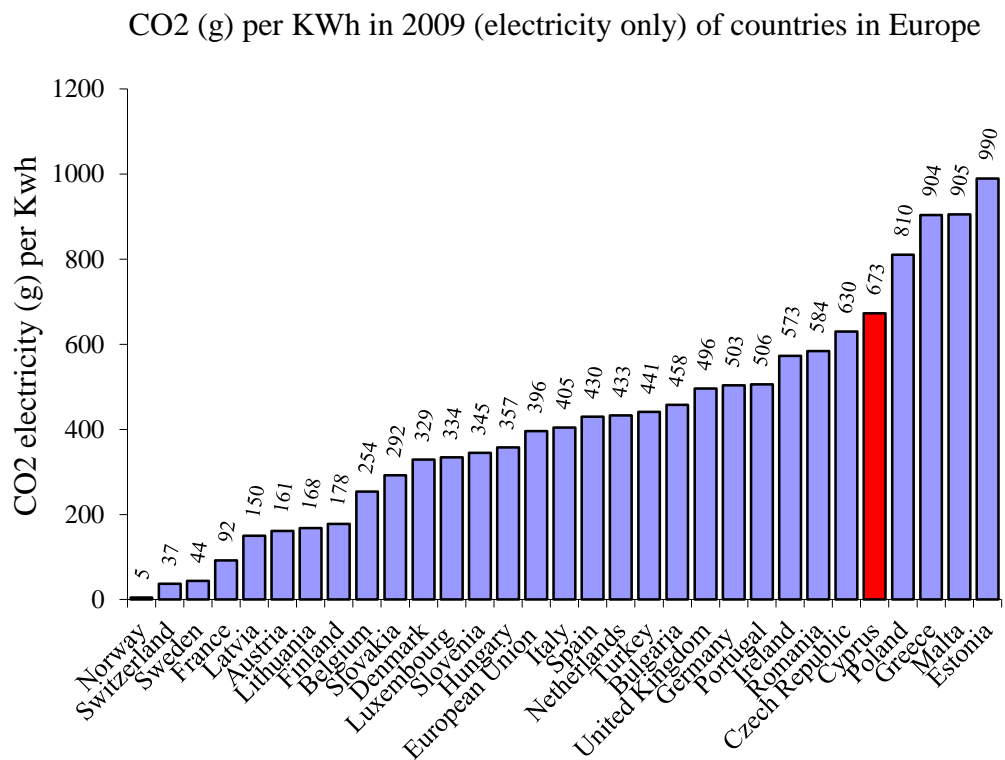


Figure 4: Emissions data of the European countries in year 2009 [17].

One of the biggest reasons of this situation is because Cyprus's electricity generation is isolated but also mainly because Cyprus is currently almost fully reliant on imported oil.

2.5. Electricity consumption of a typical household in Cyprus

The "Final Energy Consumption in Households" survey [14] was carried out by the Statistical Service of South Cyprus for the first time in 2009. This was addressed to households, whose residents had their permanent or usual residence in Cyprus, irrespective of their citizenship or country of origin. The survey sample comprised 3,300 households, distributed in all administrative districts and areas, both urban and rural, and was representative of the population structure.

On the basis of the results, a typical household in Cyprus was estimated to consume 6,288 kWh per annum in terms of electricity and other energy resources.

The annual energy consumption of a typical household for space heating was shown to comprise of 642 kWh on average in terms of electricity and other energy resources. The percentage of households that use air conditioning during the hot period of the year is high, 80.8%. On average, during the hot periods, households cool only 50 m² of the total 168 m² area of a typical residence. These units are of relatively modern, since more than 70% have been installed in the last decade. The annual energy consumption of a typical household for space cooling is 1.107 kWh of electricity, while the average installed capacity of air conditioning units per household is of the order of 9.47 kW.

The annual energy consumption of a typical household for water heating comprises on average 382 kWh of electricity plus other energy resources.

The households' energy needs for cooking purposes proved to be particularly high. The annual energy consumption of a typical household for cooking is on average 554 kWh of electricity plus other energy resources.

Considering the electricity consumption for the operation of electrical appliances and lighting, it is estimated that a typical household consumes annually 3,603 kWh. Nearly all households are equipped with a television set, 99.1%, a refrigerator-freezer, 99%, an electric iron, 96.2%, and a clothes washing machine, 93.7%. The use of satellite dishes, 29.9%, clothes dryers, 30.5% and dish washers, 44.6%, is less common. On average, appliances being more intensely used on a weekly basis are television sets, 46 hrs, computers, 31 hrs, and clothes washing machines, 7 hrs.

A summary breakdown of the electricity usage of a typical household in Cyprus according to the Final Energy consumption in Household in Cyprus in 2009 is shown in figure 5 below.

Energy Usage	Electricity (kWh)	Electricity (%)
Space Heating	642	10.21
Water Heating	382	6.08
Space Cooling	1107	17.60
Cooking	554	8.81
Electrical Appliances & Lighting	3603	57.30
TOTAL	6288	100

Figure 5: Summary of survey results of the Final Energy Consumption in Households of Cyprus conducted in 2009 [14].

2.6. Electricity demand in Cyprus

In South Cyprus domestic demand represents 36% of total electricity consumption [15] whereas this amount is 32% in the Northern Cyprus [13]. The use of electricity for street lighting is 2% for both Northern and South Cyprus. Industry, on the other hand, has higher percentage of 18% in the South Cyprus compared with 8% in the Northern Cyprus. However, the agriculture percentage is higher, 6%, in the Northern Cyprus whereas this amount is 3% in the South Cyprus. The other significant difference between two regions is the transmission and distribution losses. The claimed losses in the South Cyprus system are as low as 3%. However, this value is much higher, 15%, in the Northern Cyprus.

Figures 6 and 7 summarises the breakdown share of the electricity demand in customer types or sectors such as street lighting, industry, etc. of the year 2010 [13, 15].

SOUTH CYPRUS

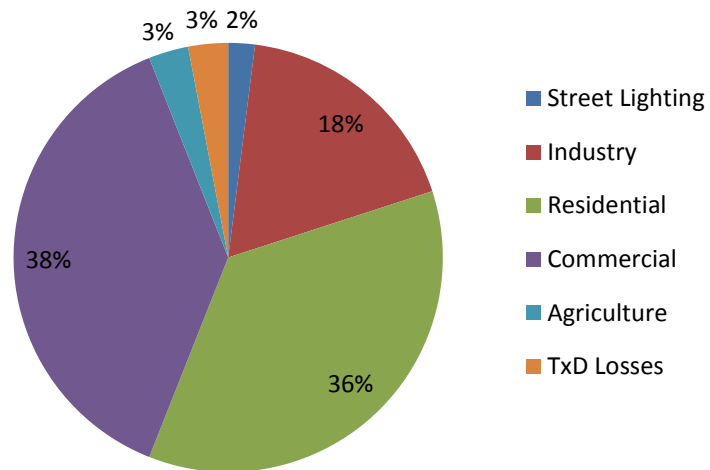


Figure 6: The breakdown of total electricity demand in terms of customer types of South Cyprus in 2010 [13].

NORTHERN CYPRUS

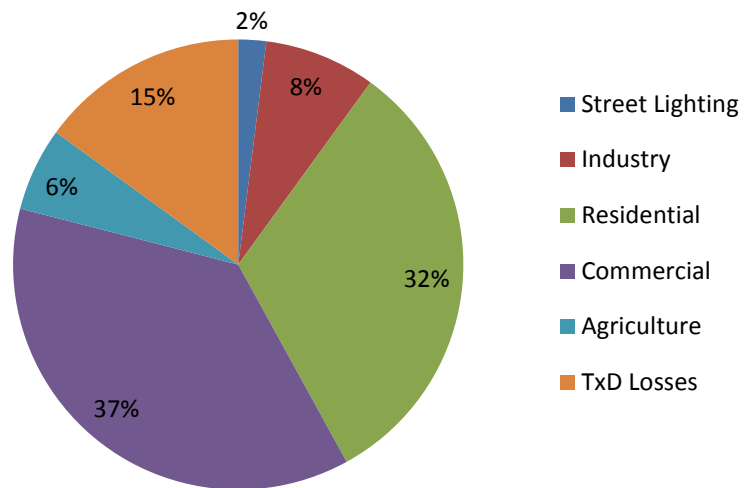


Figure 7: The breakdown of total electricity demand in terms of customer types of Northern Cyprus in 2010 [13].

From the data provided by the Electricity Authority of Northern Cyprus (KIBTEK), the electricity demand trend throughout the years between 1997 and 2010 is plotted on the figure 8 [13]. The plot also includes a trend line in order to represent the average rate of increase per annum of the demand of Northern Cyprus. The slope of the trend line is 56,799 MWh or 56 GWh per year. In year 2010, the Northern Cyprus's energy demand was 1,243 GWh and 56 GWh is equivalent of 4.5% of the total demand. With no change to this trend of increase this amount would yield to 45% increase in electricity use by the year 2020.

In addition, research by M. Ilkan et al. in 2005 concluded that the growth in annual electricity demand of the Turkish Republic of Northern Cyprus (TRNC) would be approximately 3.3% until 2020 [18]. In year 2010, the northern Cyprus's energy demand was 1,243 GWh and 3.3% is equivalent to approximately to 41,050 MWh or 41 GWh. His study suggests that the increase in demand will be approximately 26% by the year 2020.

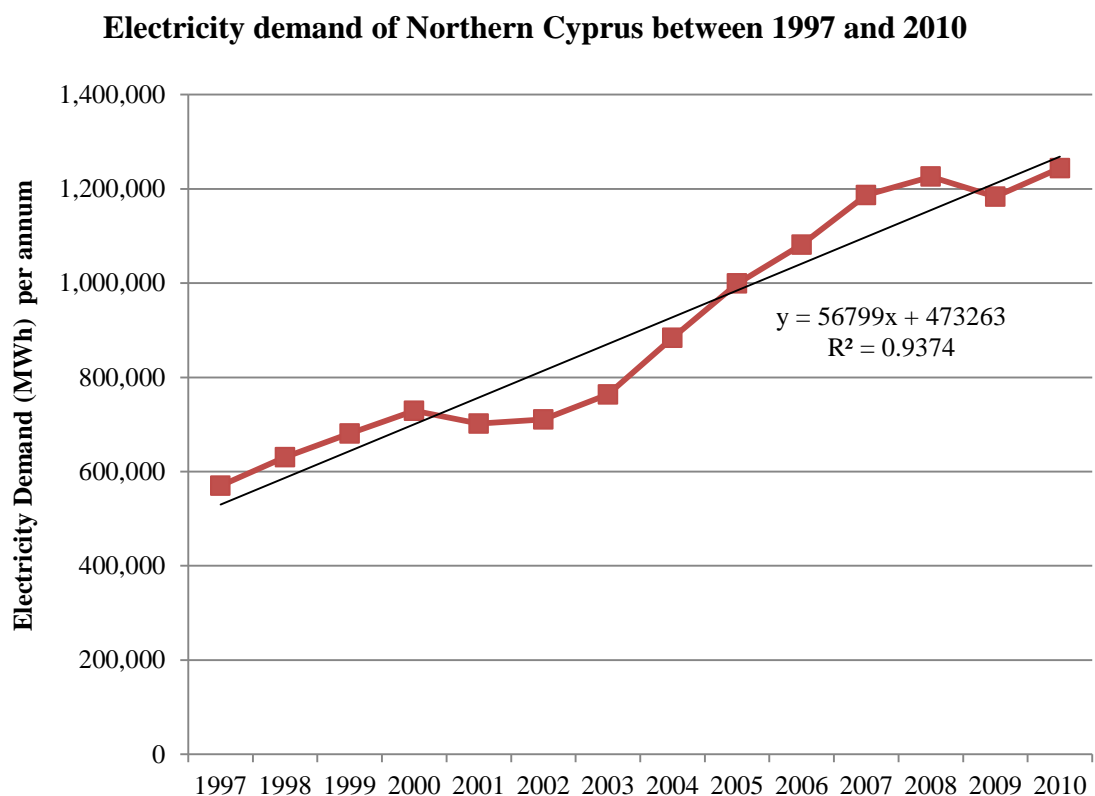


Figure 8: Electricity demand of Northern Cyprus between 1997 and 2010 shown with linear trend line.

Zachariadias studied the load growth for South Cyprus and estimated that the future load requirements due to economic growth and relative oil prices may amount to an annual increase of 5.3% until 2020 [19]. The annual report of the Electricity Authority of Cyprus (EAC) in 2008, predicted an annual increase in demand of 3.6% to 2018 [20].

From the data provided by the Electricity Authority of Cyprus (EAC), the electricity demand trend throughout the years between 2000 and 2010 is plotted on the figure 9 [20,15]. The plot also includes a trend line in order to represent the average rate of increase per annum of the demand of South Cyprus. The slope of the trend line is 202,464 MWh or 202 GWh per year. In year 2010, the South Cyprus's energy demand was 5,241 GWh and 202 GWh is equivalent of 3.86% of the total demand. With no change to this trend of increase this amount would yield to 37% increase in electricity use by the year 2020.

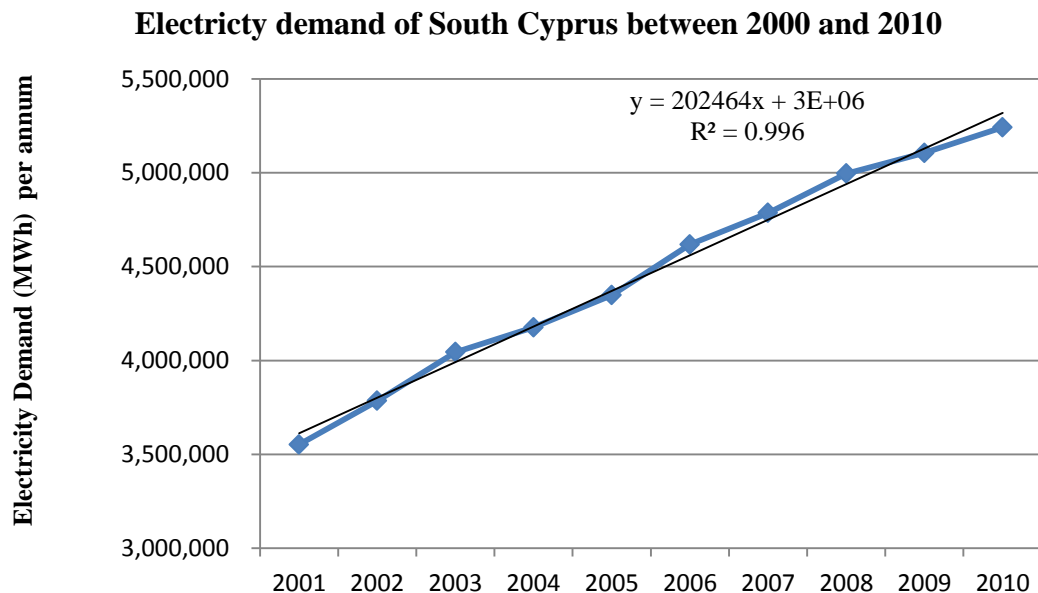


Figure 9: Electricity demand of South Cyprus between 2000 and 2010 shown with linear trend line.

The indication from the various studies and from the current trends of the electricity demand increase is that the electricity demand will be increasing in the coming years if no changes are introduced. This increase can range from 33% to 46% for the Northern Cyprus and 36% to 53% for the South Cyprus until 2020 compared with the electricity demand of the year 2010.

2.7. The EU Directives and the opportunities

Cyprus is almost entirely dependent on imports. In 2007, imports of oil products, coal and pet coke for home consumption, amounted to 1.05 million Euros, representing 16.7% of the country's domestic imports. Energy is therefore of vital importance to the Cyprus's economy. The energy consumption is predominantly oil-based and amounts to 96% of the total consumption. Other forms of commercial fuels used are solid fuels, coal and pet coke used for the production of cement, amounting to 2.0% of the total consumption. The remaining 2.0% of energy is derived from solar sources i.e. solar roof collectors. Currently, this is the only substantial contribution from renewable energy sources, in the country's energy consumption [21].

Objectives to develop RES and reduce CO₂ emissions were introduced by the European Commission and in the European Climate Change Program (ECCP). The first ECCP program was introduced in 2000 to identify the most environmentally effective and most cost-effective policies and measures that could be taken at a European level to cut greenhouse gas emissions. The Second European Climate Change Programme, ECCP II, was launched in October 2005 and has explored further cost-effective options for reducing greenhouse gas emissions [22].

Earlier, in 1997, the European Commission proposed that the EU should aim to reach a 12% share of renewable energy by 2010. Directives were adopted in the electricity and transport sectors that set national targets [23].

Among these, the target for Cyprus was to achieve a 6% share of renewable energy in electricity production by 2010 [24]. It achieved 4.3% [25]. As part of the Community targets for 2020, Cyprus has a target to achieve 13% of gross renewable energy share [23].

With the estimated increase in electricity demand, to achieve these targets and lower the high costs of imported energy, which are a burden on the economy, there needs to be a major investment in generation using renewable energy.

The following chapter investigates the potential of different renewable energy resources such as wind, solar, biomass and tidal.

CHAPTER 3

RENEWABLE ENERGY RESOURCES IN CYPRUS

This chapter investigates the potential of different renewable energy resources such as wind, solar, biomass and tidal. Due to their availability, the emphasis is given to wind and solar resources. Maps and characteristics of these sources are produced. Barriers preventing uptake of renewable energy sources are identified. Operational and ongoing wind farm projects are investigated and explored.

3. Renewable Energy Resources in Cyprus

3.1. Assessment of renewable energy resources in Cyprus

Most types of renewable energy resources have fairly established technologies and their exploitation depends mainly on the economics that apply for the particular site in question. While adequate resource has to be available with feasible costs, in addition, technical and environmental issues also play a fundamental role in the project's viability and sustainability.

Tidal energy potential has been assessed by the studies conducted by Barker and it has concluded that sites which have a mean range exceeding 3m can be exploited. Furthermore, Barker has established that none of this potential exists in the Eastern Mediterranean [26].

Lack of rivers with significant yearly flows also draws the line under the hydropower opportunity in Cyprus. Geographically there are no geothermal resources, where heat stored in rock is conveyed to the surface by means of fluids and steam, exist in Cyprus [27]. Hence, the potential for small hydro plants is very limited, especially with the water shortages over the last years. The suitable sites are estimated as being adequate for a maximum of about 1 MW installed capacity [28].

Biomass resources in Cyprus include a wide range of biomass residues, agricultural and forest, municipal solid waste, sewage water sludge and a considerable potential of energy crops, which include traditional herbaceous crops, or short rotation woody crops. A large energy potential exists from energy crops that can be grown on deforested or otherwise degraded lands. The theoretical potential is always estimated from data for the cultivated areas for each crop and the residue yield. Then the available potential can be evaluated with the assumption that only a portion of the theoretical potential is available for energy exploitation since there are other uses for most agricultural residues. Current biomass exploitation refers to a significant amount of agricultural residues in connection to the traditional wood stoves and the prospects of the development of energy crops, even though, further analysis and on site investigation may identify possible difficulties on harvesting of agricultural by-products for bioelectricity production [28].

A support scheme was developed in 2007. This scheme includes the option of a subsidy on the produced kWh from biomass and biogas. These initiations made such investments more attractive to investors and as a result, a few applications were put in place. Currently eight installations are producing electricity from the anaerobic digestion of animal waste. Their capacity is 3,55MW and the production for the 2009 was around 25 GWh. It was estimated that the electricity production from biomass will be about 1.4% of the total electricity consumption in the year 2010. In addition, 0.95MW are being installed and will be using the municipal sewage to produce electricity [162].

Regarding the wind potential (on-shore), in Cyprus there are some areas with mean wind velocity of 5-6 m/s and few areas with 6.5-7m/s. Utilization of wind energy in Cyprus is affected by anticyclones moving from west to east, from the Siberian anticyclone during the winter and from the low pressure crated in the area of India and expanded until the area of Cyprus during the summer; sea breezes generated in coastal areas as a result of the different heat capacities of sea and land, which give rise to different rates of heating and cooling; and mountain valley winds created when cool mountain air warms up in the morning and begins to rise while cool air from the valley moves to replace it. During the night the flow reverses [28].

The prospect of installing wind turbines in the Southern coast of Cyprus (near shore applications) is currently been investigated. Initial studies showed that due to the high depth of the sea at relatively short distance from the shore, more that 30m depth at a distance of 300 m from the shore, the cost of the installation of the offshore wind turbines is expected to be very high, to the extent that the wind potential which exists at those areas will not be enough to compensate the investment [28].

Concerning solar energy potential, the Meteorological service of Cyprus has classified the Island in 14 zones from a climatic point of view. However, from the considerations, affecting the use of solar energy, the classification may be broadened to 3 zones – coastal, central plains and mountains. The collection of sunshine duration data at a number of meteorological stations started in 1959. Statistical analysis shows that all parts of Cyprus enjoy a sunny climate [28].

3.2. Wind resource in Cyprus

Cyprus is surrounded by the Mediterranean Sea. Its climate is characterized as two distinct seasons. First; the rainy season, from November to March, in which the island is under the influence of depressions crossing the Mediterranean Sea, from west to east. Second; a long dry season which is from the beginning of April and lasts to the end of October while the island is subjected to the shallow low pressure trough which extends from continental depression centred over Asia. However, in coastal areas the local sea-breeze circulation is usually very strong due to a large differential heating between sea and land [29, 30].

For estimating the wind energy potential of a site, the wind data collected from the location needs to be properly analyzed and interpreted. Long term wind data from the meteorological stations near to the candidate site can be used for making preliminary estimates. This data then should be carefully extrapolated to represent the wind profile at potential site.

Meteorological services under the Ministry of Agriculture of South Cyprus have compiled a mean annual wind speed map of island of Cyprus. The compiled map is formed using the mean annual wind speed (m/s) for the period from 1982 to 1992 [44]. This map is shown at figure 10. From this map is can be observed that plain areas of the island has mainly mean wind speed range of 3 to 4 m/s. Areas near at the coast bays has mean speed range of 4 to 5 m/s.

At figure 11, topological map of Cyprus is shown [45]. By comparing two maps, from figure 10 and 11, it can be observed that higher grounds or mountainous areas have mean wind speeds ranging mainly higher than 4 m/s and lower than 7 m/s.

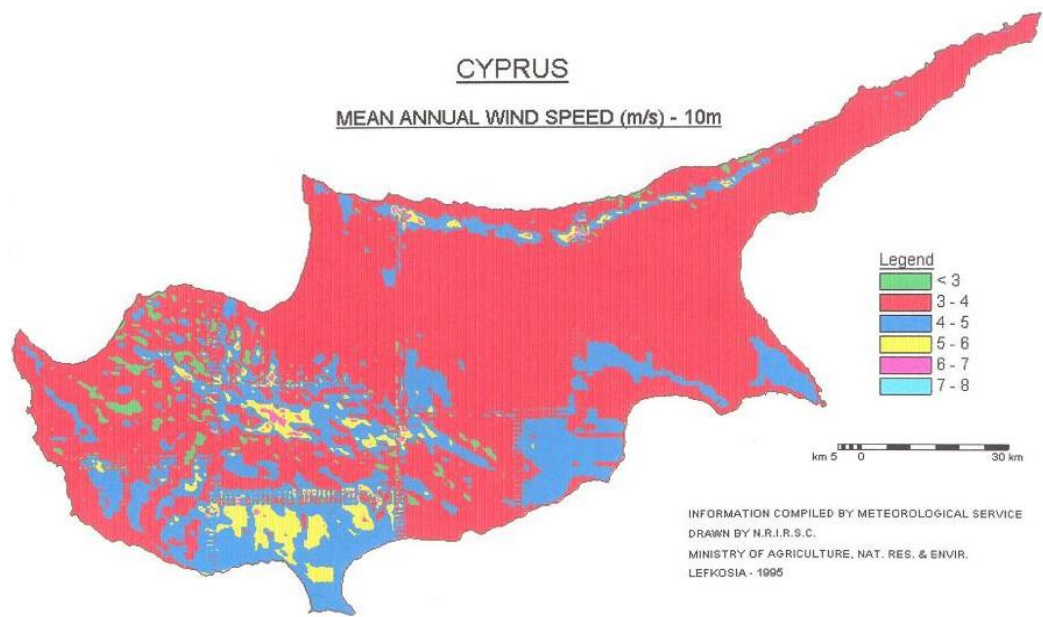


Figure 10: Mean annual wind speed (m/s) for the period from 1982 to 1992 of Cyprus [44]



Figure 11: Topological map of Cyprus [45]

In order to be able to assess the wind potential of Cyprus, data from well spread sites on the island is gathered from publications of Jacovides et al [29] and Pashardes et al [30]. Also, 5 years' data from well established internet based weather database has also been collated [31]. The chosen sites are represented on the map in figure 12.



Figure 12: Map of metered wind data on the island

In order to be able to graphically represent the long years of data into single graph, within this study, the Weibull distribution, in which the variations in wind velocity are characterized by two functions, the probability density function and cumulative distribution function, is used.

The probability density function, $f(V)$, indicates the fraction of time(or probability) for which the wind is at a given velocity (V). The probability density function is given by:-

$$f(V) = \frac{k}{c} \left(\frac{V}{c} \right)^{k-1} e^{-\left(\frac{V}{c} \right)^k} \quad (1)$$

In the equation 1, k is the Weibull shape factor and c is scale factor. For a unit area of the rotor, power available (P_v) in the wind stream of velocity V is given by:-

$$P_v = \frac{1}{2} \rho_a V^3 \quad (2)$$

The fraction of time for which this velocity V prevails in the regime is given by $f(V)$. The energy per unit time contributed by V is PV times $f(V)$.

Thus the total energy, contributed by all possible velocities in the wind regime, available for a unit rotor area and time may be expressed as:-

$$E_D = \int_0^{\infty} P_v f(V) dV \quad (3)$$

The above expression can not be resolved analytically. Numerical methods are to be adopted for solving these equations. The software called Wind Energy Resource Analysis (WERA) is used to analyze the chosen sites [32]. WERA uses the graphical method which transforms the cumulative distribution function into a linear function by adopting logarithmic scales.

Figure 13 is tabulated from the results of this analysis produced by WERA by using hourly mean wind speeds of each site as an input to the software. The column of the table which is labelled as VF_{\max} (m/s) represents the most frequent wind velocity, and respectively VE_{\max} (m/s) represents the velocity contributing the maximum energy to the regime. The peak of the probability density curve represents the VF_{\max} (m/s). Due to the cubic velocity power relationship of wind, the velocity contributing the maximum energy is usually higher than the most frequent wind velocity. Wind energy conversion systems (WECS) operate at its maximum efficiency at its design velocity wind velocity. Hence, it is advantageous that design wind velocity is chosen close to the VE_{\max} .

Assessing the energy available in the wind regime prevailing at a site is one of the preliminary steps in the planning of a wind energy project. Wind energy density and the energy available in the regime over a period are the major steps involved in evaluating the energy potential. In this case, the column named Energy Density (ED) (kW/m^2) is the energy density and it is the energy available in the regime for a unit rotor area and time. Thus it's a function of the velocity and distribution of wind in the regime. Energy Intensity (EI) (kWh/m^2 per annum) is the total energy available in the spectra. It is calculated by multiplying ED by the time factor that is 8760 hours for an annum.

Station Name	k	c	VFmax (m/s)	VEmax (m/s)	Energy Density (kW/m^2)	Energy Intensity (kWh/m^2) per year
Paphos	2.87	4.43	3.82	5.33	0.0545	477.72
Larnaca	2.87	3.67	3.16	4.41	0.0310	271.62
Paralimni	2.16	4.86	3.64	6.58	0.0871	762.77
Limassol	1.94	3.64	2.51	5.24	0.0408	357.1
Akrotiri	2.11	4.18	3.08	5.73	0.0566	495.89
Athalassa	2.91	4.68	4.05	5.6	0.0639	559.64
Ercan	2.91	4.65	4.02	5.57	0.0627	548.94
Polis	1.92	3.76	2.56	5.45	0.0455	398.25

Figure 13: Tabulated results generated using WERA and collated wind data of above sites.

The values calculated at above using the collated wind data at above sites are substituted into the probability density function (equation 1). The results are graphically represented at figure 14 at below.

On the other hand, figure 15, is the graphical representation of the Energy Intensity column per chosen site. Among the sites Paralimni has the highest value of energy intensity at 762 kWh/m^2 per annum and Larnaca has the lowest at a value of 271 kWh/m^2 per annum.

Weibull distribution function of each chosen site in Cyprus

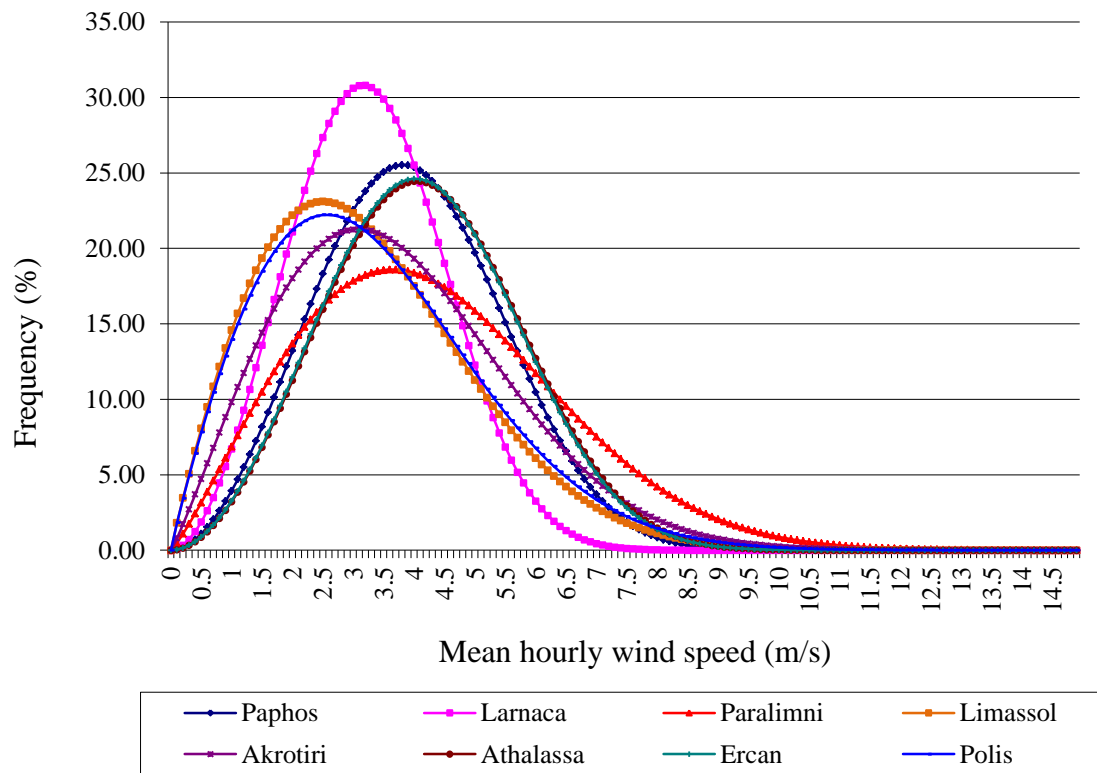


Figure 14: Weibull distribution function of each chosen site in Cyprus.

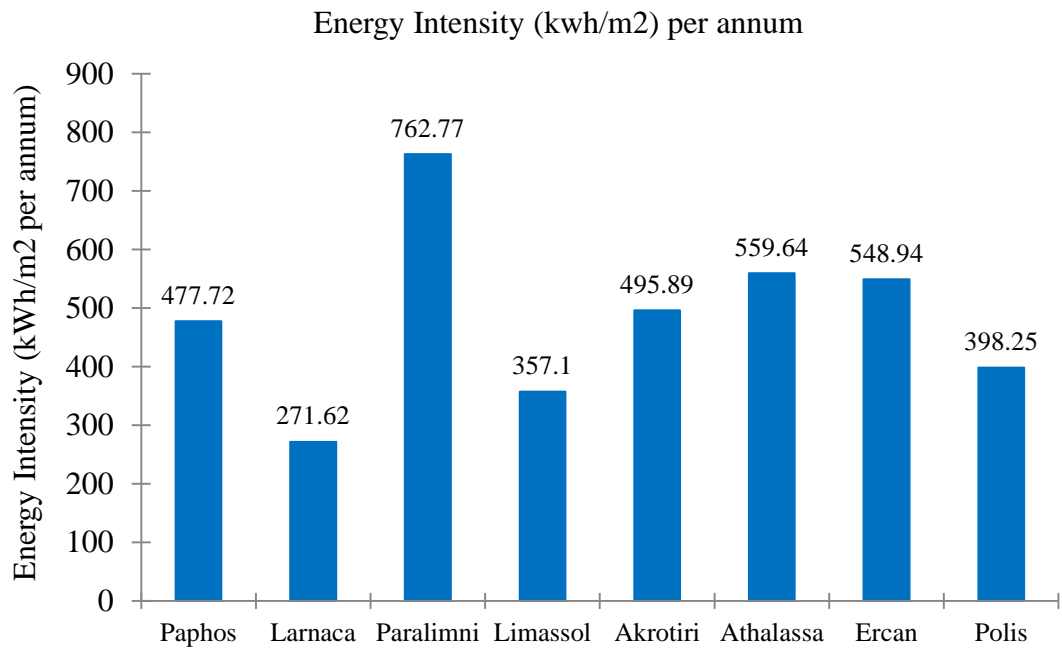


Figure 15: The graphical representation of the Energy Intensity column per chosen site.

Throughout the world, there are special group of wind turbine manufactures whose turbines constitute approximately 97% of the cumulative installed world wind power. Throughout the last decade these companies have been the top ten shareholders of cumulative installed wind capacity and their share has changed marginally with time [33, 34, 35, 36 and 37] and because of that their turbines` properties can be used as viables in the models to estimate theoretical load factor of the chosen sites in Cyprus.

In order to create a generic model of these wind turbines, the data of wind turbines manufactured by these 6 of top ten manufacturers from 2004 to 2007 has been collated in figure 16. This table simply tabulates the rated power (MW) against the rotor diameter (m) [38, 39, 40, 41, 42 and 43]. From this table, an important ratio can be deduced, namely the amount of energy produced per annum (8760hrs) if run at rated power per each m² of the total swept area covered by rotor. The average of these ratios is 3197kWh per m² and it is shown figure 17.

Using the information calculated using wind turbine data, 3197 kWh/m² per annum is the energy intensity of an average wind turbine if working at rated power all the time. However, from figure 13 and 15 it can be observed that in the terms of energy intensity, only fraction of this value are available at chosen sites.

In practice, each site would have been analyzed against a particular wind turbine with matching VE_{max} and VF_{max} where feasible. Other factors such as turbine siting and land shear factors would have been considered into these calculations. However, in order to create a theoretical picture of the wind potential at these chosen sites, load factors at each site can be calculated using the average figure from the figure 17.

Therefore from these figures the wind farm load factor can be calculated. As an example, any wind farm build at Paralimni would have load factor of:

$$\text{Load factor (LF)} = \frac{EI \text{ (kWh/m}^2 \text{ per annum)}}{E_{max} \times (\text{kWh/m}^2 \text{ per annum)}} \quad (4)$$

$$LF_{\text{Paralimni}} = 762.77 / 3197 = 23.85 \%$$

Company	Model	Rated Power	Rotor Diameter (m)
VESTAS	V112	3.00	112
	V100	1.80	100
	V90	1.80	90
	V90	1.80	90
	V90	2.00	90
	V90	3.00	90
	V80	2.00	80
	V80	2.00	80
	V82	1.65	82
	V52	0.85	52
GAMESA	G90	2.20	90
	G87	2.00	87
	G80	2.00	80
	G58	0.85	58
	G52	0.85	52
GE	3.6	3.60	111
	2.5	2.50	100
	1.5sle	1.50	77
	1.5xle	1.50	82.5
ENERCON	E82	2	82
	E70	2.3	71
	E53	0.8	52.9
	E48	0.8	48
	E44	0.9	44
	E33	0.33	33.4
SUZLON	S88-2.1	2.1	88
	S82-1.5	1.5	82
	S64-1.25	1.25	64
	S66-1.25	1.25	66
	S52-600	0.6	52
SIEMENS	SWT-3.6-107	3.6	107
	SWT-2.3-101	2.3	101
	SWT-2.3-93	2.3	93
	SWT-2.3-82	2.3	82.4
	SWT-1.3-62	1.3	62

Figure 16: Wind turbines produced by 6 of top ten manufacturers from 2004 to 2007 and their rotor diameter against rated power [38, 39, 40, 41, 42 and 43]

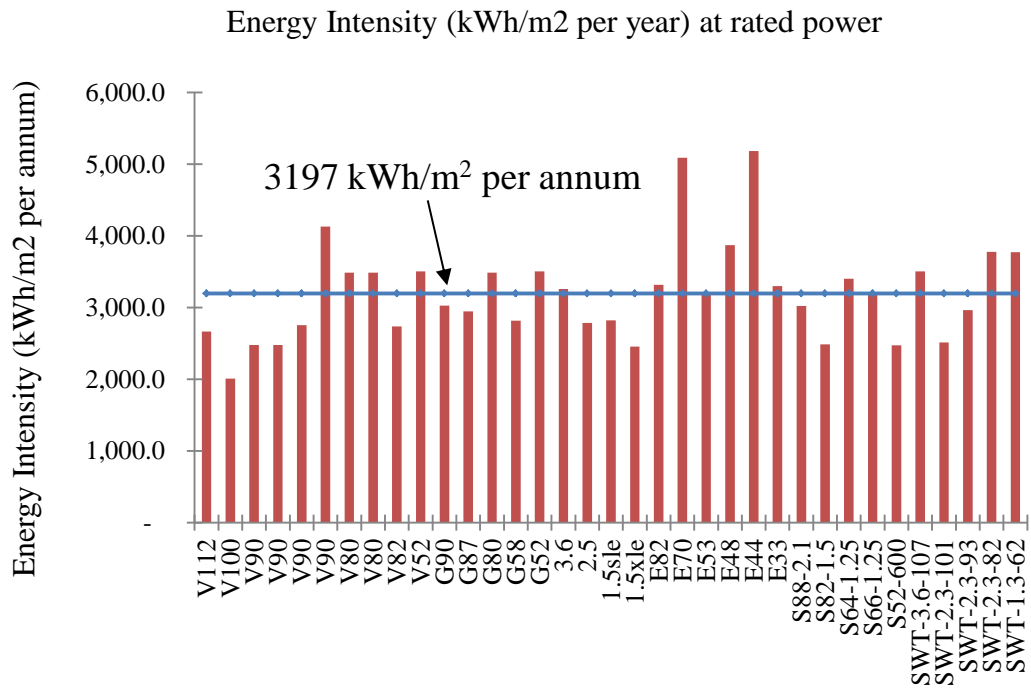


Figure 17: Ratios between the amounts of energy produced per annum (8760hrs) if run at rated power per each m² of the total swept area covered by rotor of each particular turbine of top manufacturers.

Station Name	Energy Intensity (kWh/m ²) per year	Load Factor (%)
Paphos	477.72	14.9 %
Larnaca	271.62	8.4%
Paralimni	762.77	23.85%
Limassol	357.1	11.2%
Akrotiri	495.89	15.5%
Athalassa	559.64	17.5%
Ercan	548.94	17.2%
Polis	398.25	12.5%

Figure 18: Theoretically calculated load factors at each site can be calculated using the average figure from the figure 17.

3.3. Wind power generation in Cyprus

As of present, since 2004, 25 applications for wind parks with a total capacity of approximately 515 MW have been approved by the Cyprus Energy Regulatory Authority (CERA) [47].

However, due to the difficulty in the commencement of construction of wind parks because of significant barriers that exists for the incorporation of the wind energy in the Cyprus energy system, to date there are only few projects that have signed a Connection Agreement with TSO and only one is operational and few are under construction.

These barriers can be due to the prevailing practice, lack of experience in technology or investment risks.

Wind farm projects are one of the “first of this kind” in Cyprus as at present. Despite the fact that projects are approved by the CERA, the final regulations referring to town planning/building laws for wind farms have not been enacted yet and are still being followed as guiding principles only.

Also, current electricity production in Cyprus is operated by the electricity authorities. A privately operated large wind generation systems are again not known experience within the Cyprus’s power industry. In the terms of wind farm operator, the wind farm will be one of the very first commercially operated project and staffing and knowledge infrastructures regarding construction, operations and maintenance has to start from scratch which will be leading to increased training costs. In addition, the projects will introduce technology from abroad. All material and even crane facilities for erection of the turbines will have to be imported, leading to higher costs.

Regarding the investment barriers, due to perceived risks associated with wind energy in Cyprus where there is no financial experience regarding the implementation and operation of wind farms, and in view of the rather low wind speed regime known to prevail in Cyprus, it has been proven quite difficult to attract investors and also get debt funding. Also, financial institutions lacking experience of these types of investments, perceive higher risks associated with the operation and maintenance of the equipment, making it difficult for the project to gain loans for operations and maintenance.

To overcome these barriers companies are choosing to register the projects under the clean development mechanism (CDM). The CDM executive board supervises the Kyoto Protocols CDM under the authority and guidance of the CMP. Conference of the Parties serving as the meeting of the Parties to the Kyoto Protocol (CMP) reviews the implementation of the Kyoto Protocol and takes decisions to promote its effective implementation. The CDM Executive Board is the ultimate point of contact for CDM project participants for the registration of projects and the issuance of certified emission reductions [46].

CDM registration will have the following impacts such as creation of an additional income stream from the sale of certified emission reduction (CER), substantially increasing the economic attractiveness of the project. The risk of financing would be lowered since uncertainties of income would be lowered with the CER income and defined CER contract length. Creation of the additional income stream is expected to help in securing the finance of the project at all and on better terms than otherwise would have been possible.

Also, another impact would be the increased interest of foreign participants in the project. Once successfully registered as a CDM project, there will be interest and activity in order to buy the CERs.

Therefore, following the initiatives of the European Directives, following the considerations and approval process under the CDM protocols, various wind generation projects has been privately funded in the South Cyprus. The information regarding these projects is currently publicly available via United Nations Framework Convention on Climate Change (UNFCCC) website for CDM projects [46].

Figure 19 illustrates the sizes and locations of the wind farms which have signed a connection agreement with TSO in South Cyprus. Most of these wind farms are within the Larnaca province. Nicosia on the other hand only has single wind farm.

At the moment, there are no wind farms either under construction or operational in Northern Cyprus.

List of CDM registered projects either operational or under construction in South Cyprus are summarized in the figure 20 [46]. This table is populated from the project design documents downloaded via CDM website. It can be seen that the biggest wind farm is the Orites wind farm with 72 of 2MW turbines totalling to 144MW of capacity. Currently, this is the only wind farm that has been operating for at least 1 year [48]. From the table it can be observed that short term measured mean wind speeds at high altitudes range from 4.7 m/s to 6.7 m/s yielding capacity factors of wind farms from 16% to 25%. It should be noted that these values are similar to the theoretical values calculated earlier in the previous section using metered data at various sites.

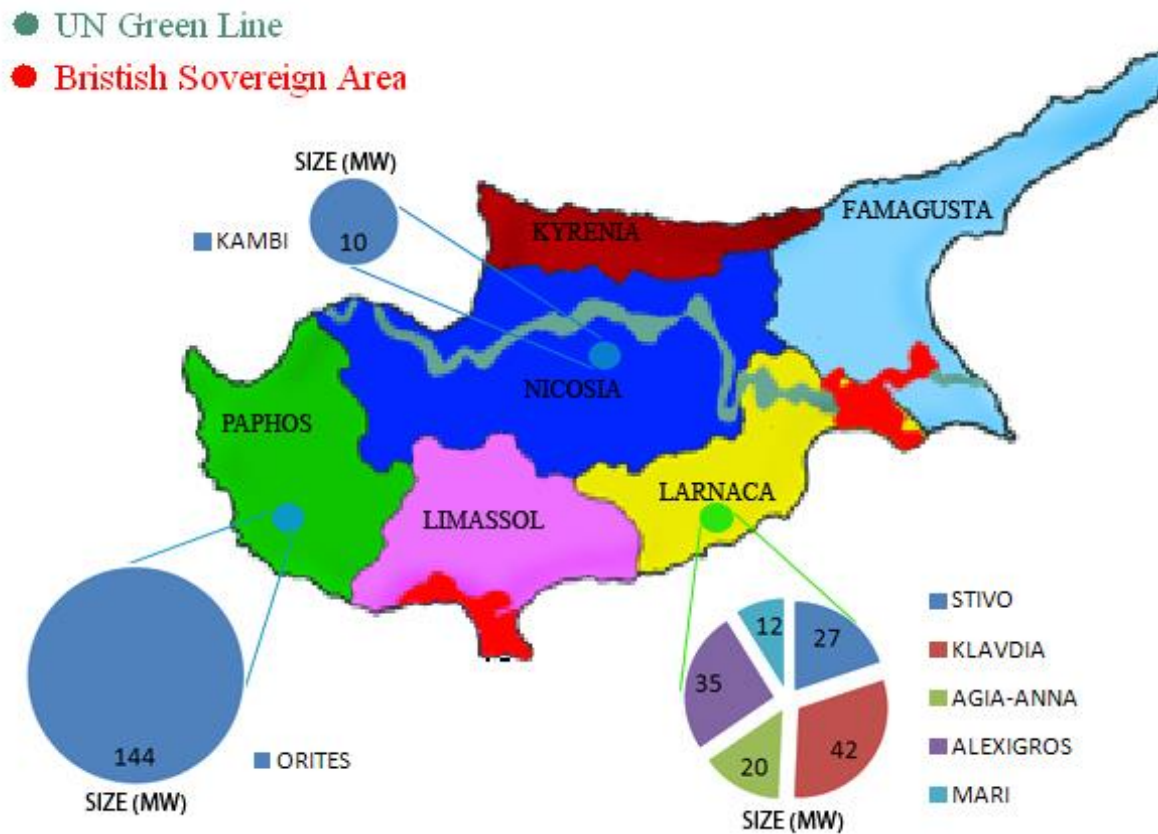


Figure 19: Locations of the wind farms currently either under construction or operational in South Cyprus [46].

Wind Farm	KAMBI	STIVO	KLAVDIA	AGIA-ANNA	ALEXI_GROS	ORITES	MARI
Province	Nicosia	Larnaca	Larnaca	Larnaca	Larnaca	Paphos	Larnaca
Number of Turbines	12	15	21	10	23	72	8
Turbine Supplier	Enercon	Vestas	Gamesa	Gamesa	VENSYS-CKD	Vestas	VENSYS-CKD
Model	E53	V100	G90	G90	VENSYS 77	V90	VENSYS 77
Rated Power	0.8 MW	1.8 MW	2 MW	2 MW	1.5 MW	2 MW	1.5 MW
Total Capacity	9.6 MW	27 MW	42 MW	20 MW	34.5 MW	144 MW	12 MW
Measured Site Wind Speed	5.7m/s at 50m	~NA	5.82 m/s at 78m	5.85 m/s at 78m	6.7 m/s at 85m	5.85 m/s at 85m	4.9 m/s at 50m
Calculated Load Factor	18.70%	16.70%	16.19%	17.61%	25.10%	16.90%	20.18%
Calculated Annual Production	15,726 MWh	39,385 MWh	59,580 MWh	30,860 MWh	76,002 MWh	213,920 MWh	21,219 MWh
CER period	10	10	10	10	7	10	3 x 7 = 21
Estimated annual tCO ₂ reductions	12,864 tonnes	30,399 tonnes	45,884 tonnes	23,778 tonnes	58,427 tonnes	174,990 tonnes	16,313 tonnes
Total estimated tCO ₂ reductions	128,640 tonnes	303,990 tonnes	458,840 tonnes	237,783 tonnes	408,988 tonnes	1,749,899 tonnes	114,190 tonnes
Selling price to EAC (c€/kWh)	9.23 c€/kWh	16.08 c€/kWh	12.97 c€/kWh	16.6 c€/kWh	9.18 c€/kWh	9.23 c€/kWh	9.18 c€/kWh
Total investment (million €)	13.5	48.8	73.7	35.1	NA	236.3	NA

Figure 20: List of CDM registered projects either operational or under construction in South Cyprus [46].

3.4. Solar resource in Cyprus

The map of global horizontal irradiation of Cyprus based on annual average sunshine from April 2004 to March 2010 provided by SolarGIS database [49] is shown in figure 21.

The average annual solar radiation received on a horizontal surface across Cyprus is 1725 kWh/m² per year. Of this amount, 69% reaches the surface as direct solar radiation, 1188 kWh/m², and 31% as diffuse radiation, 537 kWh/m² [50]. Using solar technology for power generation, the annual solar potential for properly sited power plants is estimated to be between 1950 kWh/m² and 2050 kWh/m² per year [51].

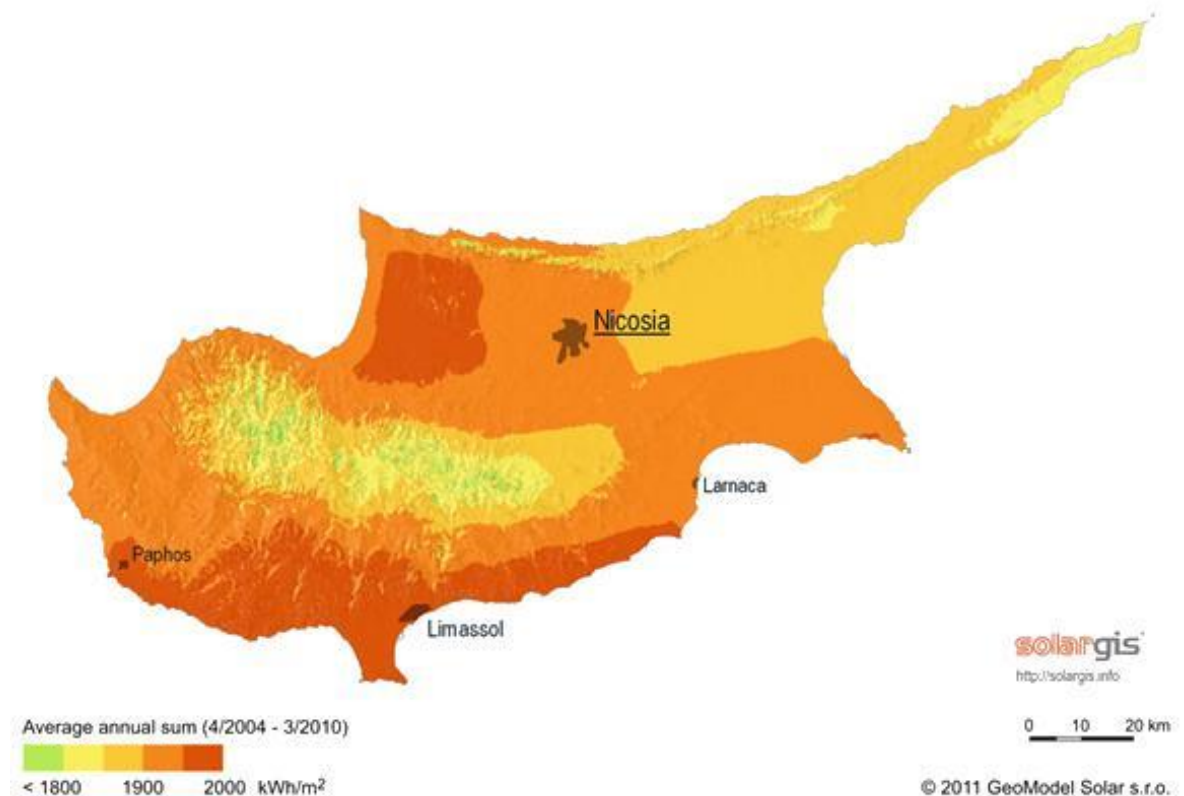


Figure 21: The map of global horizontal irradiation of Cyprus based on annual average sunshine from April 2004 to March 2010 provided by SolarGIS database [49].

By utilizing this energy, Cyprus has become the highest user of solar water heaters in Europe. The European Solar Thermal Industry Federation ranks Cyprus as the leader in installed solar collectors per capita. With more than 900,000 m² of installed solar collectors, there is the potential to produce almost 700,000 kWh of thermal energy. Cyprus has more than double the number of installed solar thermal collectors and produces twice the energy using these systems than the next European user, Austria [7].

As a study case representative, the weather file of Larnaca in EnergyPlus weather (EPW) file format has been downloaded from the international weather databases of U.S Department of Energy [52]. The site is located at 34.88° N, 33.63° E with GMT +2 hours. The weather file consists of data sets which have been constructed from the years from 1985 to 1995.

The weather data consists of parameter entries such as dry-bulb temperature, dew-point temperature, wet-bulb temperature, relative humidity, wind speed, wind direction, atmospheric pressure, global horizontal radiation, direct normal radiation, direct horizontal radiation, albedo, and snow depth. Each of these listed entries is used to form and condense to a representative and typical one year profile of 8760hours.

The global horizontal radiation of the Larnaca's weather data is pictorially represented in figure 22. This graphic shows the global solar radiation profile throughout the year per hours of the each day of each month. For example, it can be observed that in summer, solar time is from 6am until 6pm and the global horizontal radiation peaks midday at up to 1000W/m².

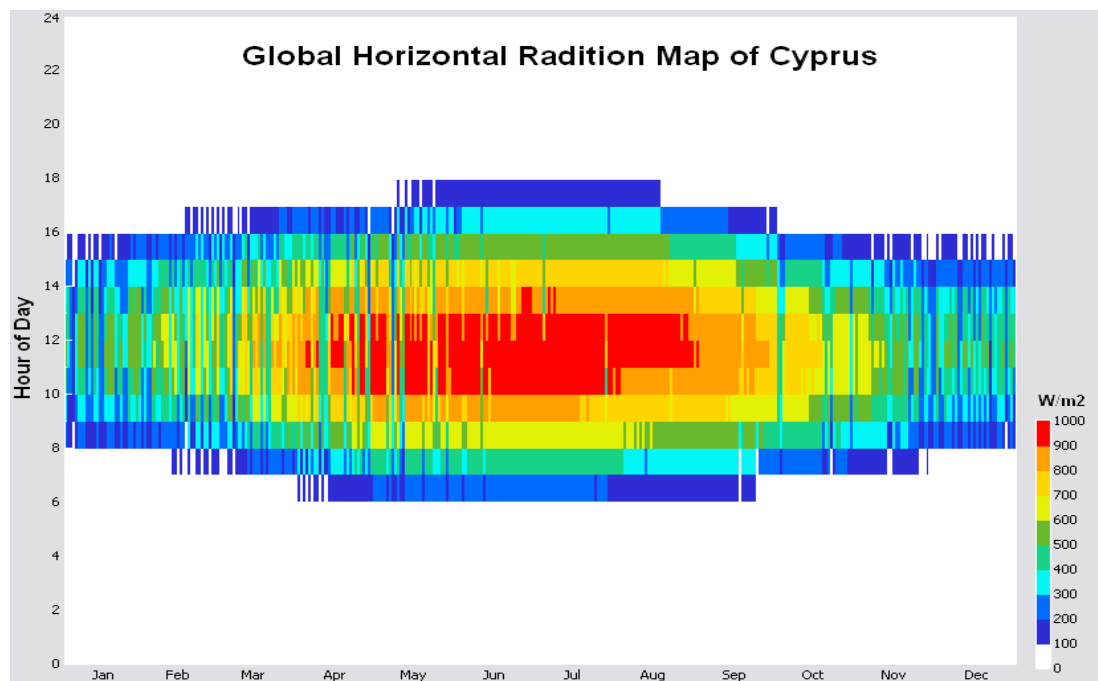


Figure 22: Global Horizontal Radiation Map of Cyprus. Hourly mean data downloaded from the international weather databases of U.S Department of Energy [52].

Continuous global horizontal radiation map of Cyprus is shown in figure 23. From this graph it can be observed that global horizontal solar radiation levels are the lowest at around $\sim 450 \text{ W/m}^2$ during winter season. However, the radiation levels steadily increase approaching to summer season and peaks in June/July at around $\sim 950 \text{ W/m}^2$. This steady pattern of solar radiation that this creates constitutes as a predictive resource to be exploited via solar energy conversion systems. On the other hand, from the sudden drops in the radiation levels on the plot, it can be observed that during the winter, spring and autumn seasons the weather is cloudier compared to summer season (June, July and August). This however, requires more extensive weather forecasting tools or weather monitoring systems for large solar energy conversion systems. Clouds in the sky creating partial shadows on photovoltaic systems or blocking direct beam radiation for concentrated solar systems will lower the performance or overall output of the solar energy conversion system.

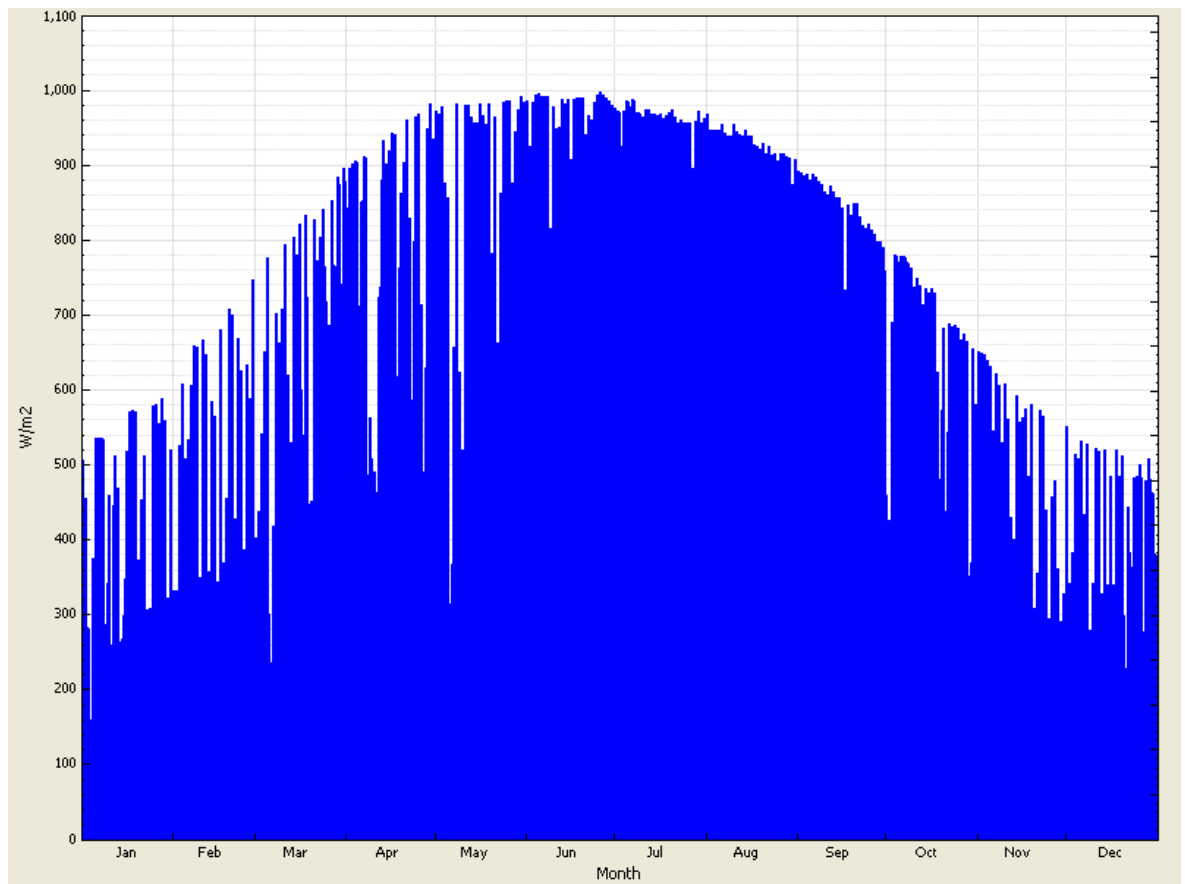


Figure 23: Continuous monthly Global Horizontal Radiation Map of Cyprus. Hourly mean data downloaded from the international weather databases of U.S Department of Energy [52]

Averaged daily global horizontal radiation map for each month is shown in figure 24. Similar to figure 22, the duration of the solar day and peak hours of days of each month can be observed. The duration of solar day is almost 12 hours in summer whereas it is in range of 8 to 9 hours in winter season. The solar radiation levels also pick up as the season changes from winter to summer from levels of $\sim 450 \text{ W/m}^2$ to levels of $\sim 950 \text{ W/m}^2$ respectively.

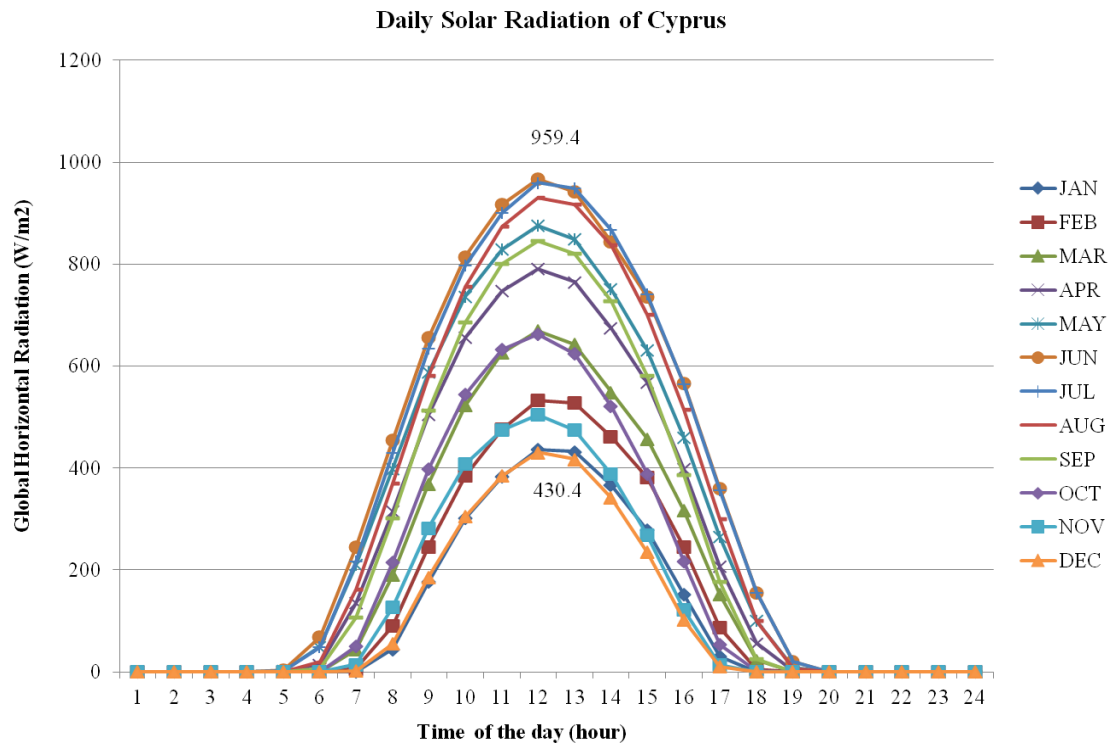


Figure 24: Averaged daily global horizontal radiation map of each month of Cyprus. Hourly mean data downloaded from the international weather databases of U.S Department of Energy [52].

Solar energy has been heavily exploited in Cyprus for many years, albeit not for bulk electricity generation. To date, solar generation projects have been under commercial or personal use with levels up to $20\text{kW}_{\text{peak}}$ with no option to sell electricity to the grid. However, there is no utility scale solar to electricity generation project connected to the Cyprus electricity system.

CHAPTER 4

RENEWABLE ENERGY TECHNOLOGIES

This chapter introduces different technologies for exploiting solar and wind energy. It compares each technology providing insight to their inner workings, pros and cons. It also provides examples with their technical details around the world where these technologies are implemented.

4. Renewable Energy Technologies

Solar energy is the energy force that sustains life on earth for all plants, animals and people. The earth receives this energy from the sun in the form of electromagnetic waves, which the sun continually emits into space. Solar capture can be investigated under two major headings. One is the mechanical way which is called solar thermal energy and the second one is by using semiconductors and is called Photovoltaic (PV) energy.

In comparison to wind power, solar output is available when the sun shines. This cycle is also temporally correlated with certain segments of electricity demand because a typical summer load such as air conditioning is mainly correlated with the weather i.e. the solar output. Therefore the capacity credit is high for locations where the summer peak load is higher than the winter peak loading, and vice versa [53].

4.1. Solar Thermal Technologies

Solar-thermal energy is perhaps best known for the widely used low-temperature solar collectors that provide residential hot water and space heating. This chapter deals with Concentrating Solar Power (CSP) systems for electricity generation, also referred to as solar-thermal power. The basic idea is to concentrate sunlight onto receivers, where it heats a heat transfer fluid (for example molten salt or oil) to a temperature sufficient to generate steam to drive a turbine and this turbine to drive electrical generator [54, 55 (p. 22)].

The main challenge for solar concentrating power is to reduce any cost, for example by improving performance and long-term reliability at reduced material input [54, 55 (p.16)]. For example, the development of direct steam generation technology where direct steam generation is used in order to avoid the need for a heat transfer fluid and associated heat exchange cost and losses [54, 55 (p. 22)].

Another aspect is achieving higher outlet temperatures which would result in higher thermal conversion efficiencies [56].

Also, various designs have been proposed and implemented that involve heat storage systems using molten salts, steam, graphite, or phase-change materials. Optional longer term storage means that the plant can also produce during extended low radiation periods, thus significantly increasing its capacity credit [57].

Therefore, the anticipated cost decreases are expected to come from such technological innovation and from up-scaling [54, 58].

Concentrating Solar Power systems focus and intensify the sun's light and absorb the energy to heat a fluid to high temperature which is used to drive a turbine or engine connected to a generator. There are four primary configurations of CSP systems. Parabolic trough systems use mirrors that reflect and focus sunlight onto a linear receiver tube. Linear Fresnel systems approximate the parabolic shape of a traditional trough collector with long, ground-level rows of flat or slightly curved mirrors that reflect the solar rays onto an overhead, downward-facing linear receiver. Power tower systems use numerous tracking mirrors, called heliostats, which reflect the sun's rays to a receiver located on top of a centrally located tower. The receiver in each of these configurations contains a fluid that is heated by the sunlight and then used to create superheated steam, which spins a turbine and drives a generator to produce electricity. Dish-engine systems use a parabolic dish of mirrors to direct and concentrate sunlight onto a central engine that produces electricity. CSP technology inherently lends itself to energy storage because the materials used to deliver energy to the energy conversion device (turbine or engine) may be held in a tank and then used to produce electricity on demand and can be extended into night time [71].

4.1.1. Solar concentration towers

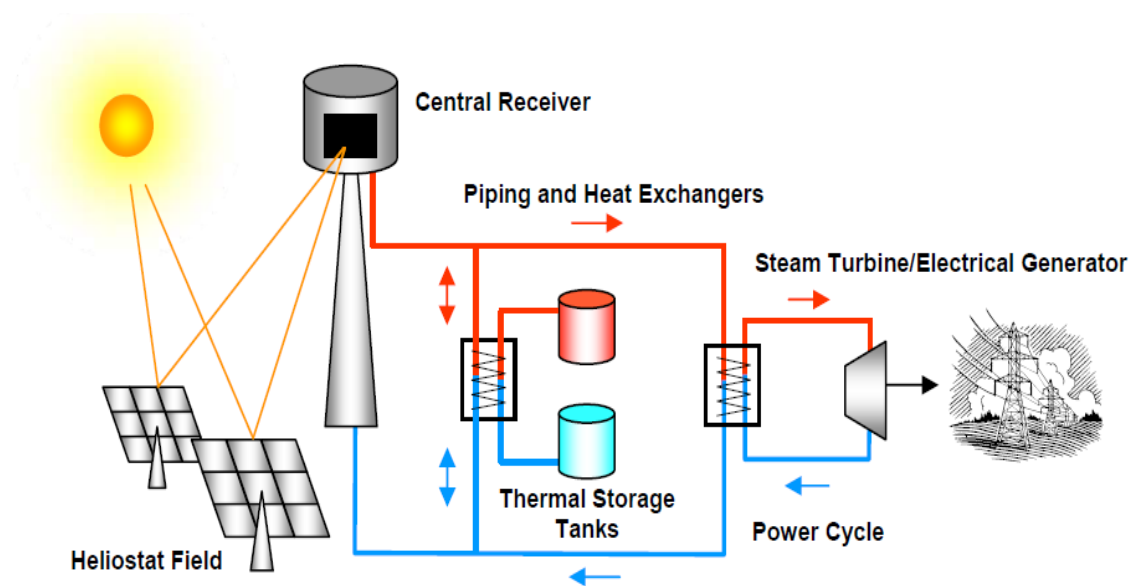


Figure 25: Principle of operation of a solar tower system. An indirect storage system is depicted [89].

The figure 25 is an illustration of a typical solar tower system. A circular array of heliostats, large mirrors with sun tracking motion, concentrates sunlight on to a central receiver mounted at the top of a tower. A heat-transfer medium in this central receiver absorbs the highly concentrated radiation reflected by the heliostats and converts it into thermal energy, which is used to generate superheated steam for the turbine. To date, the heat transfer media demonstrated include water/steam, molten salts and air. If pressurized gas or air is used at very high temperatures of about $1,000^{\circ}\text{C}$ or more as the heat transfer medium, it can even be used to directly replace natural gas in a gas turbine, making use of the excellent cycle (60% and more) of modern gas and steam combined cycles.

As of 2009, total installed capacity was 40 MW and this value has become 55 MW nowadays and there are projects which are under construction or proposed around the world totalling up to 3000 MW of capacity [61]. Projects near to completion include Ivanpah Solar Power facility in United States of America developed by Brightsource Energy company which will have a capacity of 392MW [69]. Another example is the Crescent DunesSolar Energy project again in United States of America developed by SolarReserve company will have a capacity of 110MW [70].

Compared to other solar thermal technologies, central receiver or tower systems have the following advantages [61];

- *Good mid-term prospects for high conversion efficiencies, operating temperature potential beyond 1000C proven at 10MW scale
- *Storage at high temperatures
- *Hybrid operation possible
- *Better suited for dry cooling concepts than troughs and Fresnel
- *Better options to use non-flat sites

On the other hand, solar thermal power technologies still need further research to overcome both non-technical and technical barriers. Solar thermal power plants require a long-term view in the same way as traditional energy producing plants, and therefore benefit from stable policies and continuity of legal and financial frameworks, ideally favourable for solar thermal power systems [63]. Therefore, because of the lack of commercial experience due to small number of projects, projected annual performance values, investment and operating costs need wider scale proof in commercial operation [61]. With the future investments to large plants this is expected to be remedied.

One operational example to this technology is the PS10 plant [51]. This plant is an operational solar thermal plant based on the solar tower technology. It is located in Sanlúcar de Mayor in Sevilla, Spain and began operation in 2007. The plant has a land area of 600,000 m² and it is the first solar tower plant to begin commercial electricity generation operations in the world. The plant solar tower is 100 m high, and the heliostats that track the sun on two axes, and concentrate the sun's irradiation to the focal point (receiver) located on the tower, are 624 in total with a surface area of 120 m² each. Therefore, the total reflective surface area is 75,000 m². Each heliostat has an independent solar tracking mechanism that directs solar radiation toward the receiver. The actual heliostat field does not however completely surround the receiver tower. In the northern hemisphere, the heliostat field is located on the north side of the tower to optimize the amount of solar radiation collected while minimizing heat loss. The receiver is located in the upper section of the tower. With an annual solar potential of 2100 kWh/m², and installed capacity of 11 MW, the plant is capable of generating 24.3 GWh of electricity annually (annual capacity factor of 25%).

The PS10 plant is capable of storing 1 h worth of steam for electricity generation via steam storage tanks. Steam is stored at 50 bars and 285 °C, and it condenses and flashes back to steam, when the pressure is lowered.

Additionally, under low solar irradiation conditions, the plant is capable of supplying 12–15% of its capacity via natural gas combustion. The total plant efficiency, (conversion of solar irradiation to electricity) is approximately 17%. This is a fairly high number considering that the efficiency of the steam cycle alone is approximately 27% [51].

4.1.2. Parabolic trough concentrator systems

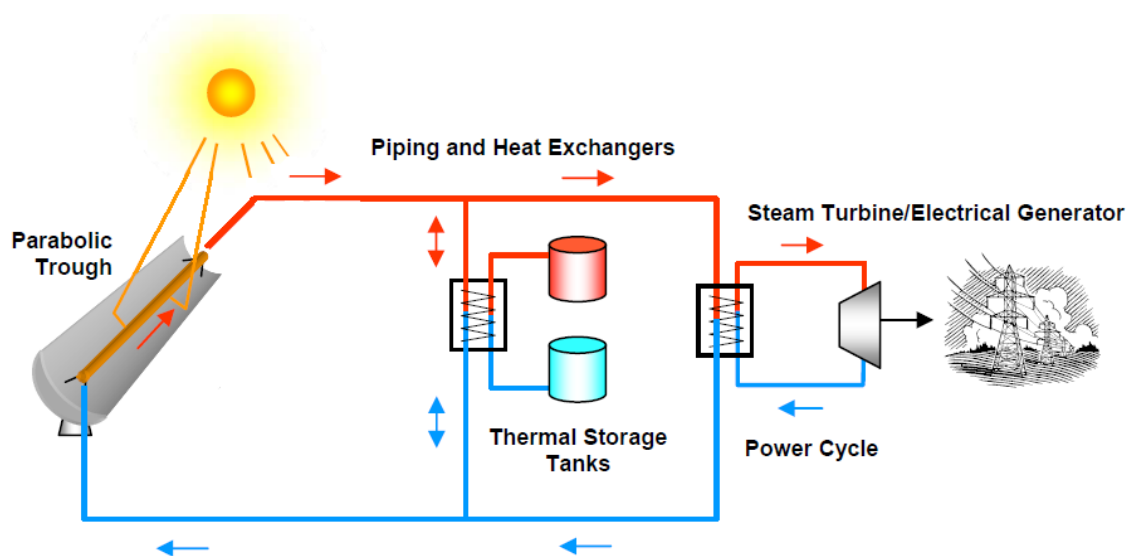


Figure 26: Principle of operation of a parabolic trough system [89].

Parabolic trough-shaped mirror reflectors are used to concentrate sunlight on to thermally efficient receiver tubes placed in the trough's focal line. The troughs are usually designed to track the Sun along one axis, predominantly north–south. A thermal transfer fluid, such as synthetic thermal oil, is circulated in these tubes. The fluid is heated to approximately 400°C by the sun's concentrated rays and then pumped through a series of heat exchangers to produce superheated steam. The steam is converted to electrical energy in a conventional steam turbine generator, which can either be part of a conventional steam cycle or integrated into a combined steam and gas turbine cycle [51].

The parabolic troughs along which these tubular receivers run may be 5–6 m wide, 1 m or 2 m deep and up to 150 m in length (though an individual trough of this length will usually be constructed from modular sections). Many of these are required to collect sufficient energy to provide heat for a single power plant [51]. As a consequence, these solar troughs form a physically large part of the solar plant and their cost can have a significant impact on plant economics. Parabolic solar troughs are usually aligned with their long axes from north to south and they are mounted on supports that allow them to track the sun from east to west across the sky. These supports may be made of steel or aluminium.

In the first commercial plants the actual mirrors were made from 4 mm glass which is both heavy and expensive. Modern developments aim to reduce the cost and weight by using new techniques and materials including polished aluminium instead of coated glass mirrors [51].

On July 1997, the SEGS VI plant (located in Kramer Junction, California) reached its all time single day performance record, averaging 18% efficiency over the day and 20% between 9 a.m. and 5 p.m. [60]. The figure 26 is an illustration of a typical parabolic trough system.

This is currently the most deployed technology, with about 1.6 GW installed all over the world and about 2.6 GW in construction. These plants are being built with a power output between a few megawatts to almost 200 MW, but the most common are the 50MW units constructed in Spain (due to an administrative regulation which limit the power to 50 MW in order to access to feed in tariffs). The optimum power output could be around 125 MW [72].

Compared to other concentrating solar thermal technologies, parabolic trough technology systems have the following advantages [61];

- * Commercially available - over 16 billion kWh of operational experience; operating temperature up to 500°C (400°C commercially proven)
- * Commercially proven annual net plant efficiency 14% (solar to electricity)
- * Commercially proven investment and operating costs
- * Modularity
- * Lowest materials demand
- * Hybrid concept proven
- * Storage capability

On the other hand, technically compared to tower systems, because of the use of oil-based heat transfer media restricts operating temperatures today to 400°C, resulting in only moderate steam qualities, hence lowering the overall efficiency of the plant [61].

Few examples to the operational plants to date would include the Solar Electric Generating Systems (SEGS), Nevada One and Andasol Plants [51].

The Solar Electric Generating System (SEGS) is the largest solar energy generating facility in the world. It consists of nine solar power plants, located at Mohave Desert, in California, USA, with an annual solar potential of 2700 kWh/m². The plants have a total of 354MW installed capacity, with a gross average output for all nine plants around 75 MW. In addition, the turbines can be utilized at night by burning natural gas. The combined solar field has a total parabolic reflecting mirror area of over 2 million m² and the nine SEGS plants cover a land area of more than 6,400,000 m². The SEGS installation uses parabolic trough technology along with natural gas to generate electricity.

Lined up, the parabolic mirrors would extend to over 369 km. and around 90% of its electricity output is produced by the sunlight. Natural gas is only used when the solar power is insufficient to meet the electricity demand of southern California. The installation uses synthetic oil as heat transfer fluid which heats to over 400°C, transferring its heat to generate steam from water, in order to drive a Rankine cycle steam turbine thereby generating electricity [51].

Nevada Solar One is located in the El Dorado Valley in Nevada, USA. The solar field is made up of 760 solar parabolic trough collectors, each with a reflective surface of 470 m^2 , to make up a total of $357,200 \text{ m}^2$ of solar reflective field, over a total land area of $1,600,000 \text{ m}^2$. The steam turbine has a nominal generating capacity of 64MW and the plant produces annually around 130 GWh (annual capacity factor of 23%), while employing a supplementary gas heater facility for back-up steam generation in case solar irradiation is not adequate [51].

Andasol 1 and 2 are two identical solar thermal plants expected to begin operations very soon and will then be the first solar thermal parabolic trough power plants to operate in Europe. These two 50MW plants are located in Andalusia, Spain [51]. The Andasol 1 solar thermal plant consists of three basic parts: the solar field, the storage tanks and the power generation block. The solar field of each of the Andasol plant uses 624 parabolic mirrors arranged in 156 loops with a total reflective area of more than $510,120 \text{ m}^2$ in a land area of $2,000,000 \text{ m}^2$. Andasol 1 is estimated to supply annual electricity generation of 179 GWh. With an annual solar potential of 2201 kWh/m^2 , total solar field annual average efficiency (efficiency of solar irradiance conversion to solar steam) is estimated around 43%, while the steam cycle efficiency is estimated to be 38.1%. Overall plant efficiency is thus around 16%. The Andasol plants are the first solar thermal plants to utilize two molten salt storage tanks for heat storage in cases of low solar irradiation. Heat storage begins to occur at midday, when the sun irradiation is very high and electricity can be generated while, at the same time, the heat storage system can be charged. In order to charge the storage system, heat from the heat transfer fluid is transferred to the molten salt tank which collects the heat while the molten salt moves from the cold tank to the hot tank, where it accumulates until it is completely full. When heat is to be discharged, the salt cools down and moves to the cold tank. Since the cold and hot salts are kept in two separate tanks, this is called a two-tank system. The molten salt storage tank system increases the annual equivalent full-load running time of the solar thermal plant to around 3500 h. The two storage tanks have a diameter of 36 m and a height of 14 m each and have a storage capacity of 7.5 h at 50 MW. The quantity of the molten salts employed is estimated to be 28,500 t, with a melting temperature of 221°C and allowed operational temperature range between 291°C (cold tank) and 384°C (hot tank) [51].

4.1.3. Parabolic dish concentrator systems

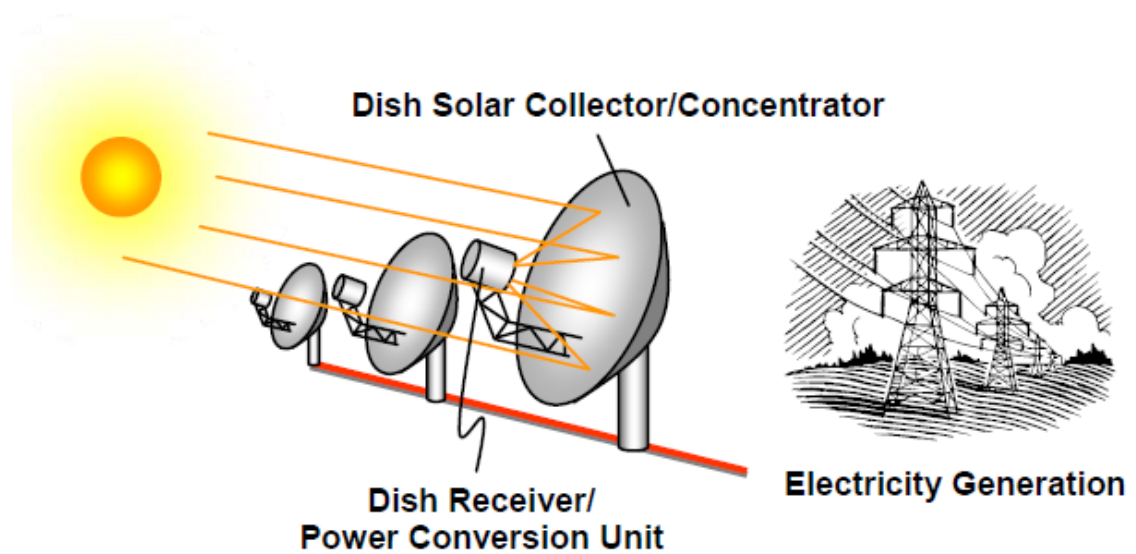


Figure 27: Principle of operation of a solar dish system [59].

A parabolic dish-shaped reflector concentrates sunlight on to a receiver located at the focal point of the dish. The concentrated beam radiation is absorbed into a receiver to heat a fluid or gas (air) to approximately 750°C [51]. This fluid or gas is then used to generate electricity in a small piston or Stirling engine or a micro turbine, attached to the receiver. The reflectors are usually designed to track the Sun along one axis, predominantly north–south [51].

Typical dishes are between 5 m and 10 m in diameter and with reflective areas of 40–120 m², though they have been built as large as 400 m².

Material limitations are likely to restrict the practical size of dishes though dishes up to 15 m in diameter (700 m²) have been proposed. Dishes in this size range could provide up to 50 kW of power. However, today Stirling engines are limited to 25 kW [51].

Stirling engines, given the right materials, can be made to operate at temperatures of up to 1000 °C, with consequent higher efficiencies than steam engines. Current experimental solar energy systems using these have managed very high overall conversion efficiencies, approaching 30% on average over the day [60]. The figure 27 is an illustration of a typical solar dish system.

To this date, there are very small numbers of operational projects. These projects are mainly serving demonstration or proof of concept purposes along with electricity generation.

Compared to other concentrating solar thermal technologies, dish technology has the following advantages [51];

- * Very high conversion efficiencies - peak solar to electric conversion over 30%
- * Modularity
- * Easily manufactured and mass-produced from available parts
- * No water requirements for cooling the cycle

On the other hand, there are major caveats such as;

- * No large-scale commercial examples
- * Projected cost goals of mass production still to be proven
- * Lower dispatchability potential for grid integration
- * Hybrid receivers still an R&D goal

One operational example of this technology is the Maricopa solar project. This plant consists of 60 individual dish and tracker system, called SunCatchers, creating a combined capacity of 1.5 MW. The plant site is located in Arizona, United States of America and began operation in January 2010. The claimed annual solar to electricity gross efficiency is up to 26% [73].

4.1.4. Linear Fresnel Reflector (LFR)

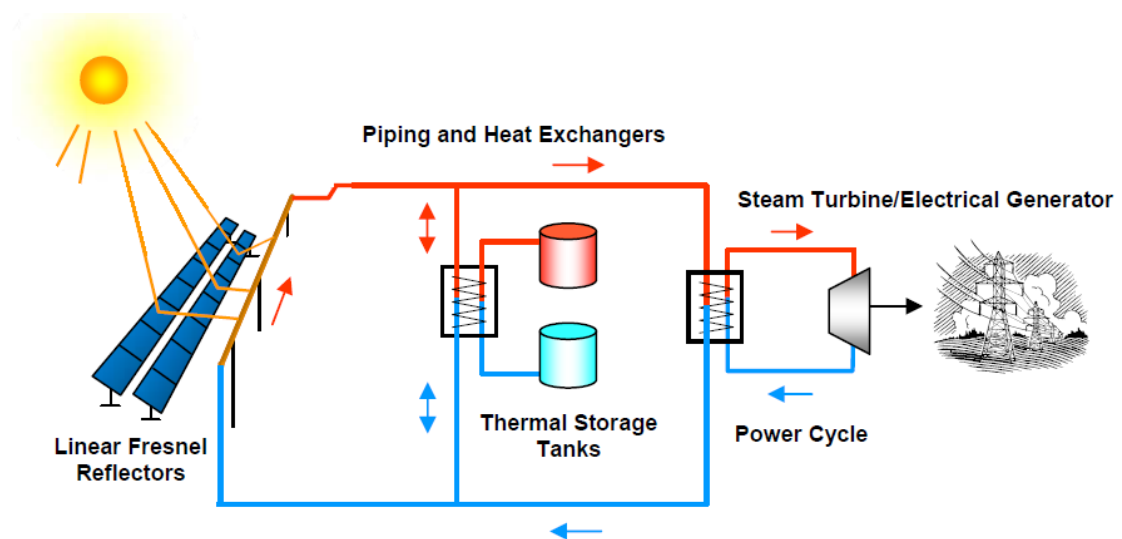


Figure 28: A typical linear Fresnel reflector [89].

LFR technology is similar to solar trough technology. Sunlight is reflected by a series of mirrors onto a receiver tube. Instead of using a parabolic shaped mirror, however, the “parabola” in LFR is divided into ten or more flat mirrors that each rotate to follow the sun [62]. This arrangement enables the mirrors to remain near the ground to avoid wind loads. In addition, by use of fixed fluid joints, a receiver separated from the reflector system and long focal lengths that allow the use of flat mirrors avoids the higher costs of both the curved mirrors and the specialized receiver tubes of trough systems [61].

The receiver tubes in the case of LFR contain water, and the plant creates saturated steam at about 545°F that drives a turbine to generate electricity [62]. The technology is seen as a potentially lower-cost alternative to trough technology for the production of solar process heat [61]. The figure 28 is an illustration of a typical linear Fresnel reflector system [61].

Main advantages of using this technology are as follows;

- * Building materials (steel, mirrors etc.) are readily available
- * Flat mirrors can be purchased and bent on site, lower manufacturing costs
- * Hybrid operation possible
- * Very high space efficiency around solar noon

On the other hand due being a recent market entrant to the concentrating technologies market and due only small projects operating this technology is not considered matured.

One example to an operational LFR technology is Kimberlina Solar Thermal Power Plant located in California, United States of America. The plant has started its operation in October 2008 and has gross capacity of 5 MW [74].

4.2. Photovoltaic Technology

Rapid progress in increasing the efficiency and reducing the cost of PV cells has been made over the past few decades. Their terrestrial uses are now widespread, particularly in providing power for telecommunications, lighting and other electrical appliances in remote locations where a more conventional electricity supply would be too costly.

A single conventional PV cell produces only about 1.5 watts, so to obtain more power, groups of cells are normally connected together to form rectangular modules. To obtain even more power, modules are in turn mounted side by side and connected together to form arrays.

A growing number of domestic, commercial and industrial buildings now have PV arrays providing a proportion of their energy needs. The basic component of a PV power system is the photovoltaic or solar cell. The cell is encapsulated and wired in a so-called PV module, which is commercially sold. Modules are mounted on rooftops, posts or other structures, sometimes in solar arrays. In grid-connected applications, an inverter is needed to transform the cell's DC output into AC. Off-grid applications can work with DC, but need a storage system (for example a battery) and a charge controller.

There are a number of cell types that are distinguished by their material properties. Crystalline silicon cells are produced from melting of PV grade silicon; these account for the majority of PV production and applications [64].

Single-crystal PV cells are produced by growing a single crystal, whilst multi-crystalline cells are manufactured in a melting and solidification process.

Multi-crystalline cells are less expensive than single-crystal cells, but because of the interfaces between the crystals, their commercial conversion efficiency is lower. Cells are produced by sawing ingots or ribbons into wafers.

Since light is converted into electric charge only in a thin surface layer of the cell, one way of reducing cell costs are thin film cells. These are produced by deposition of PV semiconductor material (amorphous silicon, cadmium telluride CdTe, and copper-indium-gallium-arsenide compounds CIGS) onto a glass, plastic or metal substrate.

The figure 29 summarizes the published best measurements for cells and sub-modules efficiencies measured under the global spectrum (1000 W/m²) at 25°C which were published in “Solar cell efficiency tables (version 37)” [64].

Cell Type	Efficiency (%)	Description
Si (amorphous)	10.1 +/-0.3	Oerlikon Solar Lab, Neuchatel
Si (crystalline)	25.0 +/-0.5	UNSW PERL
Si (multicrystalline)	20.4 +/-0.5	FhG-ISE
Si (thin film transfer)	16.7 +/-0.4	U. Stuttgart (45 mm thick)
Si (thin film submodule)	10.5 +/-0.3	CSG Solar (1–2 mm on glass; 20 cells)
GaAs (thin film)	27.6 +/-0.8	Alta Devices
GaAs (multicrystalline)	18.4 +/-0.5	RTI, Ge substrate
CIGS (cell)	19.6 +/-0.6	NREL, CIGS on glass
CIGS (submodule)	16.7 +/-0.4	U. Uppsala, 4 serial cells
CdTe (cell)	16.7 +/-0.5	NREL, mesa on glass
CdTe (submodule)	12.5 +/-0.4	ASP Hangzhou, 8 serial cells

Figure 29: Confirmed terrestrial cell and sub-module efficiencies measured under the global spectrum (1000 W/m²) at 25°C [64].

According to Bagnall and Boreland [66] future challenges in bringing kWh cost down lie with improving the performance of PV cells. Future devices will require significant improvements in efficiency not only at the laboratory scale, but at the commercial scale.

Moreover, means to exploit the entire wavelength spectrum of solar light for the excitation of carriers in PV materials are currently being explored, such as multi-bandgap multi-junction devices. Another stream of research is directed at creating light-trapping and concentrating cell surfaces. Bagnall and Boreland [66] review the state of research on emerging photovoltaic technologies. Zoellner et al. [65] reports from a survey showing that economic considerations influence the acceptance of photovoltaic power.

Large, centralized PV power systems, mostly at the multi-megawatt scale, have also been built to supply power for local or regional electricity grids in a number of countries, including Germany, Switzerland, Italy and the USA [67].

Compared with building-integrated PV systems, large stand-alone PV plants can take advantage of economies of scale in purchasing and installing large numbers of PV modules and associated equipment, and can be located on sites that are optimal in terms of solar radiation.

On the other hand, the electricity they produce is not used on-site and has to be distributed by the grid. This involves transmission losses, and the price paid for the power by a local electricity utility will usually only be the ‘wholesale’ price at which it can buy power from other sources (although in some countries such as Germany, PV power is purchased at premium prices) [67].

Large plants also require substantial areas of land, which has to be purchased or leased, adding to costs – although low-value ‘waste’ land, for example alongside motorways or railways, can be used. The land can often be used for other purposes as well as PV generation. At Kobern-Gondorf in Germany the site is used as a nature reserve for endangered species of flora and fauna. In some large PV plants, such as the 4 MW installations at Sonnen in Germany, the arrays have been mounted at least one metre above the ground, minimizing shading to the vegetation beneath and even allowing sheep to graze beneath the panels. It would also, in principle, be possible to have other forms of renewable energy generation alongside a large PV system, such as wind turbines – depending on wind conditions [67].

Large PV power plants are more economically attractive in those areas of the world that have substantially greater annual total solar radiation than northern Europe. Areas such as North Africa or Southern California not only have annual solar radiation totals more than twice those in United Kingdom, but also have clearer skies. This means that the majority of the radiation is direct, making tracking and concentrating systems effective and further increasing the annual energy output. The cost of electricity from such PV installations is likely to be less than half of that from comparable non-tracking installations [67].

As with any energy source, the cost per kilowatt-hour of energy from PV cells consists essentially of a combination of the capital cost and the running cost. The capital cost of a PV energy system includes not only the cost of the PV modules themselves, but also the so-called ‘balance of system’ (BoS) costs, i.e. the costs of the interconnection of modules to form arrays, the array support structure, land and foundations (if the array is not roof mounted), the costs of cabling, charge regulators, switching, inverters and metering, plus the cost of either storage batteries or connection to the grid.

Although the initial capital costs of PV systems are currently high, their running costs should be extremely low in comparison with those of other renewable or non-renewable energy systems.

Not only does a PV system not require any fuel but also, unlike most other renewable energy systems, it has no moving parts (except in the case of tracking systems) and requires far less maintenance than, say, a wind turbine. PV systems which include batteries, however, have additional maintenance requirements [68].

One of the largest PV power plants in Europe is the BV Neuhausen solar park in Germany. This plant has a peak capacity of 145MW and consists of 650,000 modules. The construction period took only 5 months and it has been in operation since September 2012 [75].

4.3. Wind Technologies

Wind energy is a key component in any strategy to exploit renewable resources. It has been used for many thousands of years and it is an obvious choice in the portfolio of energy sources for the generation of electricity.

With all the work done on the design of wind generators and their widespread use throughout the world, it could be assumed that the technology has matured and all of the engineering decisions have been made. This is not the case and as knowledge has increased, more questions have been raised, complications realized and answers are required.

Wind is arguably the most developed of the new renewable energies for the generation of electric power. Apart from Hydro electricity generation which many consider fully developed.

It creates a raft of challenge for the design of the generator system. There are challenges of capturing varying wind which has both varying speed and intensity and then feeding the power into grid, which is running at constant frequency (and in a predefined voltage window). Two types of wind turbines can be distinguished namely fixed speed and variable speed turbines. Until the late 1990s, most wind turbine manufacturers built constant-speed wind turbines with power levels below 1.5 MW using a multistage gearbox and a standard squirrel-cage induction generator, directly connected to the grid. Since the late 1990s, most wind turbine manufacturers have changed to variable speed wind turbines for power levels from roughly 1.5 MW, mainly to enable a more flexible match with requirements considering audible noise, power quality, and energy yield. They have used a multistage gearbox, a relatively low-cost standard doubly fed induction generator (DFIG) and a power electronic converter feeding the rotor winding with a power rating of approximately 30% of the rated power of the turbine. Since 1991, there have also been wind turbine manufacturers proposing gearless generator systems with the so called direct-drive generators, mainly to reduce failures in gearboxes and to lower maintenance problems. A power electronic converter for the full-rated power is then necessary for the grid connection. The low-speed high-torque generators and the fully rated converters for these wind turbines are expensive [181 to 192].

4.3.1. Fixed speed wind energy conversion systems (WECS)

In a fixed speed WECS, the turbine speed is determined by the grid frequency, the generator pole pairs number, the machine slip, and the gearbox ratio. A change in wind speed will not affect the turbine speed to a large extent, but has effects on the electromagnetic torque and hence, also on the electrical output power. With a fixed speed WECS, it may be necessary to use aerodynamic control of the blades to optimize the whole system performance, thus introducing additional control systems, complexities, and costs. As for the generating system, nearly all wind turbines installed at present use either one of the following systems: squirrel cage induction generator, doubly fed (wound rotor) induction generator, direct-drive synchronous generator. Using induction generators will keep an almost fixed speed (variation of 1-2%). The power is limited aerodynamically either by stall, active stall or by pitch control. A soft-starter is normally used in order to reduce the inrush current during start-up. Also a reactive power compensator is needed to reduce (almost eliminate) the reactive power demand from the turbine generators [183, 184]. It is usually done by activating continuously the capacitor banks following load variation. Those solutions are attractive due to low cost and high reliability. However, a fixed-speed system cannot extract as much energy from the wind as a variable speed topology. Today the variable speed WECS are continuously increasing their market share, because it is possible to track the changes in wind speed by adapting shaft speed and thus maintaining optimal energy generation [185].

4.3.2. Variable speed WECS

The variable speed generation system is able to store the varying incoming wind power as rotational energy, by changing the speed of the wind turbine, in this way the stress on the mechanical structure is reduced, which also leads to that the delivered electrical power becomes smoother.

The control system maintains the mechanical power at its rated value by using the Maximum Power Point Tracking technique (MPPT) [186]. These WECS are generally divided into two categories: systems with partially rated power electronics and systems with full-scale power electronics interfacing wind turbines [183, 187, 188].

Two systems in case of wind turbines with partially rated power converters are the wound rotor induction generator and a medium scale power converter with a wound-rotor induction generator. First system requires an extra resistance controlled by power electronics is added in the rotor that gives a speed range of 2 to 4%. This solution also needs a soft starter and a reactive power compensator. Second system, a medium scale power converter with a wound rotor induction generator, requires a power converter connected to the rotor through slip rings controls the rotor currents. If the generator is running super-synchronously, the electrical power is delivered through both the rotor and the stator. If the generator is running sub-synchronously the electrical power is only delivered into the rotor from the grid. A speed variation of 60% around synchronous speed may be obtained by the use of a power converter of 30% of nominal power. The other WECS category is wind turbines with a full-scale power converter between the generator and grid that gives extra losses in the power conversion but it will gain the added technical performance. This system is also known as the doubly fed induction generator (DFIG).

In the case of possible systems which uses full scale power electronics induction generator, multi-pole synchronous generator and multi-pole permanent magnet synchronous generator are used.

CHAPTER 5

INTEGRATION WITH THE ELECTRICITY SYSTEM OF CYPRUS

This chapter explores the requirements of integration of renewable energy technologies to the Cyprus's grid system. It investigates the grid codes of developed European countries and identifies mandatory codes which can be added to the current grid code of Cyprus.

5. Integration with Electricity System in Cyprus

5.1. Peak electricity demand vs. air temperature vs. solar radiation of Cyprus

Electricity demand is affected by variables such as relative humidity, cloudiness, solar radiation, wind speed, electricity price, gross domestic product growth etc. In the most of the electricity systems, the residential sector is one of the main contributors to the load peaks [76]. In the residential sector, the energy consumption depends on features of the building envelope and the occupants' behaviour as well. The latter is subject to many factors including householders' subjective comfort preferences and their socio-demographic and socio-economic characteristics [77].

Over the last decade the electric energy consumption in the residential sector has significantly increased especially in the summer season, because of the increasing use of air-conditioning (AC) systems, which has drastically changed the thermal comfort needs of urban population in the developed countries. The strong penetration of the AC systems on the market was also quickened by the sudden and rapid reduction of their cost and because of the "urban heat island" effect [78, 79 and 80]. The "urban heat island" effect is the vicious circle in terms of cooling and power demand. The extended use of air conditioners, mainly of split-unit devices, increases the heat island in densely built urban areas. The heat rejected by the compressor units contributes to warm up the outdoor air in the narrow streets, thus increasing even more the cooling demand of the buildings and further reducing the coefficient of performance of the air conditioners [80, 81].

In fact, especially in the Mediterranean countries, peaks in the electricity demand occur more frequently during the summer period than during the winter. This growing demand is being strengthened by the urban heat island effect, which results in higher air temperatures in densely built towns, thus enhancing the cooling load in commercial and residential buildings [80, 82].

Daily demand data of Cyprus are gathered from the TSO [12] and the KIBTEK [13] websites and are illustrated in figure 30. The data belongs to year 2007 and a typical day in summer (July) and winter (December). From figure 30, it is explicit that the North and South consumer demand is showing very similar behavioural patterns. The correlation of the two curves and cardinal points such as summer morning peak, summer noontime plateau and winter darkness peak should be noted.

Many studies have considered use of temperature data combined with data on humidity, wind speed, cloudiness, rainfall, solar radiation as well as data electricity price, gross domestic product growth to draw up a single formula to represent the demand of electricity [85]. When the differential between outdoor and indoor temperatures increases, the starting up of the corresponding heating or cooling equipment immediately raises the demand for energy [83].

On this basis along with the urban heat island effect, temperature stands out among the meteorological and other factors that affect electricity demand [84, 85].

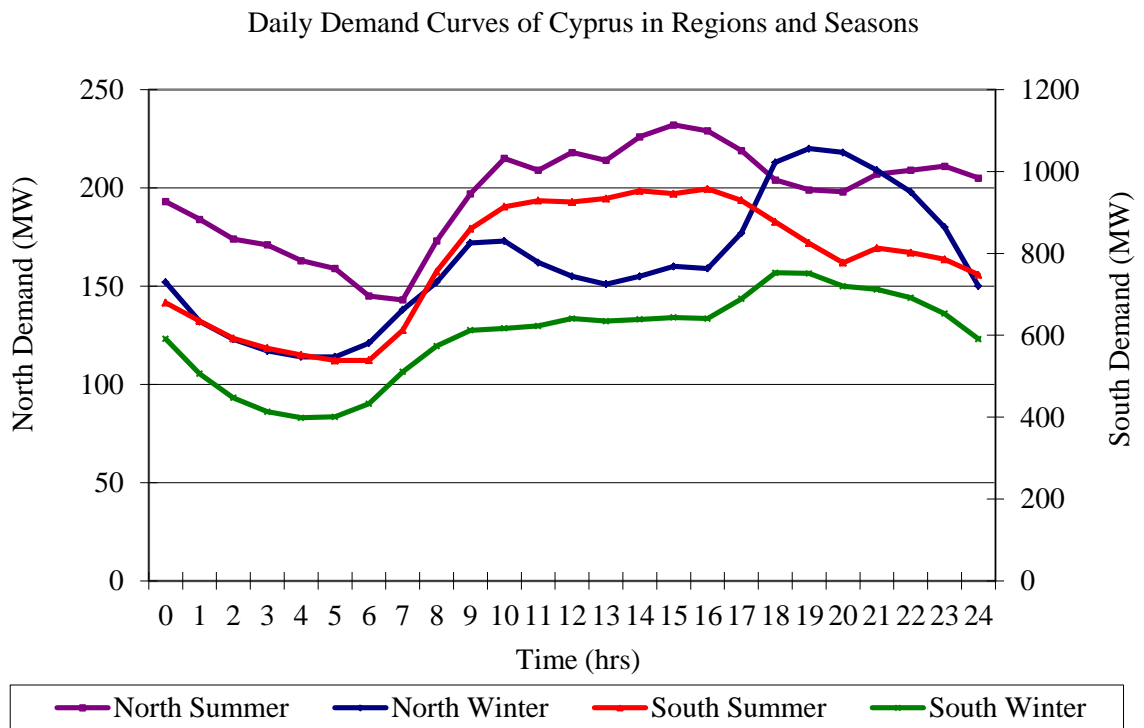


Figure 30: Daily demand curves of Cyprus according to Regions and Seasons [12, 13]

The experience of many utilities worldwide has illustrated the influence of weather in energy consumption and especially in electrical demand. In the electricity markets, it is important to understand and be able to predict the effects of natural variables on electricity demand in order to effectively manage the generation and supply of electricity [85].

The principal studies indicate that the relationship between electricity demand and temperature is clearly non-linear. This non-linearity refers to the fact that both increases and decreases of temperature, linked to the passing of “threshold” temperatures, increase the demand for electricity [84].

This response is caused by the difference between the ambient or outdoor temperature and the comfort or indoor temperature. When the differential between outdoor and indoor temperatures increases, the starting-up of the corresponding heating and cooling equipment immediately raises the demand for energy [83, 84].

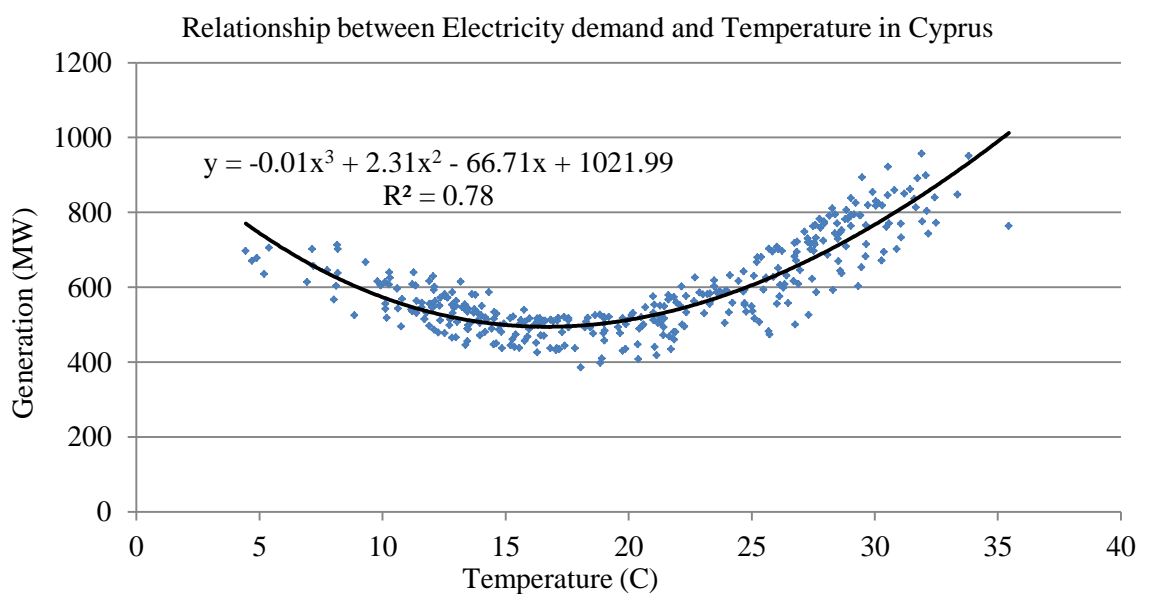


Figure 31: Relationship between electricity demand and temperature for Cyprus.

Figure 31 illustrates the relationship between electricity demand and mean daily temperatures of year 2010 for Cyprus. The raw demand and temperature data is publicly accessible and obtained from TSO of Cyprus’s website [12]. The variation of electricity demand with temperature is non-linear, increasing both for decreasing and increasing temperatures which reflects mainly use of electric or others means of heating appliances in winter and air conditioners in summer. For example, from figure 31 for year 2010, a rise in average daily temperature of 1°C from 24 °C to 25 °C would result in an increase of about 4.2% in electricity consumption. However, the demand seems to be less sensitive to temperature fluctuations in winter, since a fall in mean daily temperature of 1°C from 14 °C to 13 °C would result in an increase of about 2.1% in electricity consumption.

This is mainly attributed to the fact that final consumers can use a variety of energy sources for heating for example gas, diesel oil etc. and practically only electricity for cooling. Nevertheless, at approximately 16.7 °C, the influence of temperature is minimal and electricity demand is at its minimum at this temperature for year 2010. The balance point temperature is the outdoor air temperature causing building heat gains to be dissipated at a rate that creates a desired indoor air temperature. Any higher or lower temperatures from the balance point temperature would result to a higher electricity demand due to need of cooling or heating.

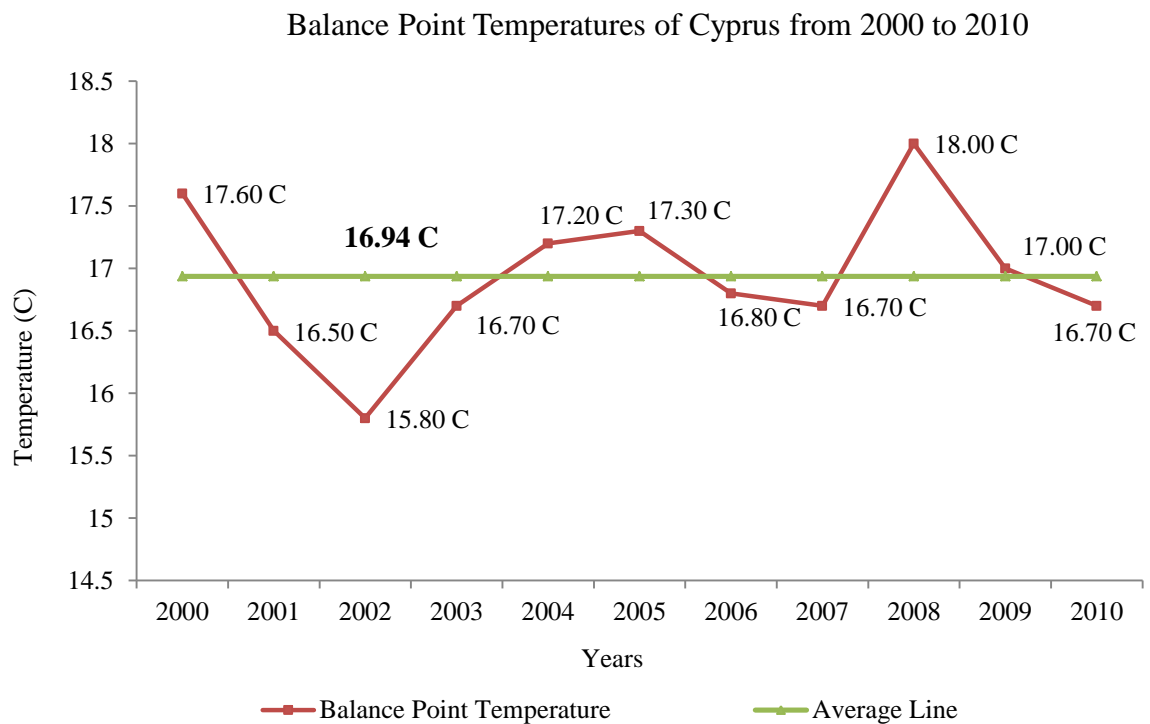


Figure 32: Balance point temperature trend of Cyprus from years 2000 to 2010

Figure 32 represents the calculated balance point temperatures of Cyprus from 2000 to 2010. The raw demand and temperature data, which is publicly accessible, obtained from TSO of Cyprus's website for years from 2000 to 2010 [12]. Each year's data is represented as in figure 31 and each year's balance point temperature is identified accordingly. There are fluctuations of the balance point temperature of Cyprus throughout these years. Nevertheless, the average balance point temperature throughout these years is 16.9 °C. This value is 16 °C for Athens [24] and 18.7 °C for Italy [80].

The amount of radiation at any particular location varies both throughout the year (annually) and throughout the day (diurnally). Annual fluctuations are associated with the sun's changing declination and hence with the seasons. Diurnal changes are related to the rotation of Earth about its axis [87].

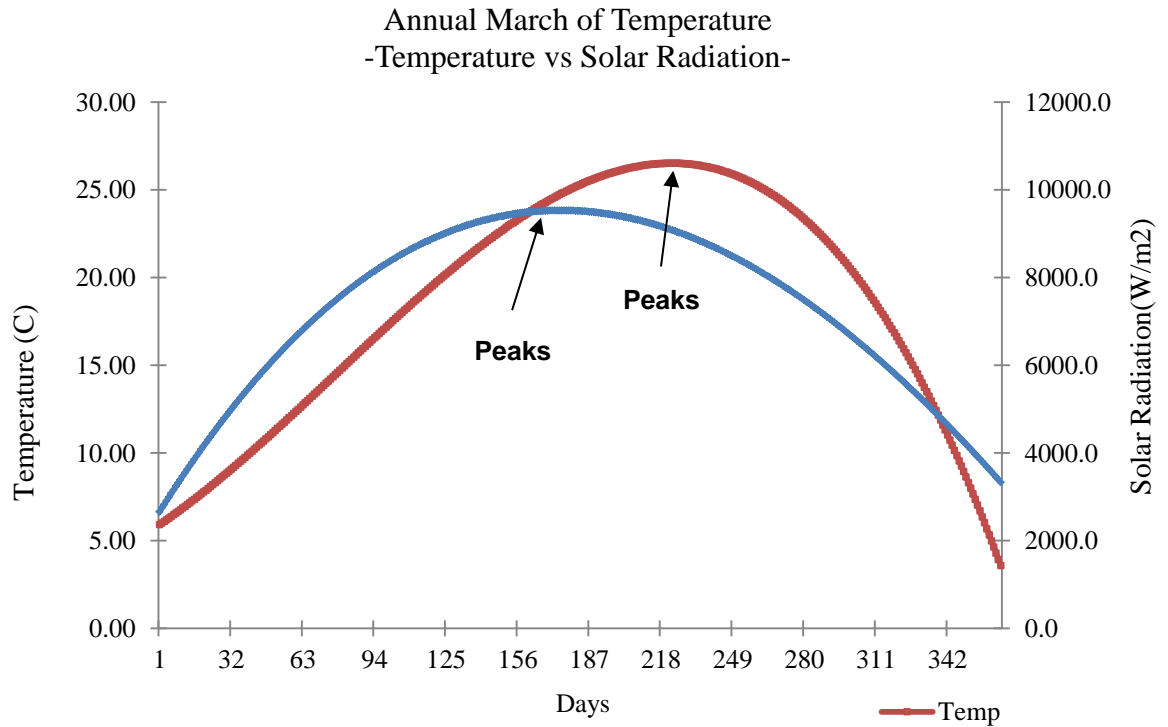


Figure 33: Annual March of Temperature of Cyprus for year 2005

The temperature data obtained from TSO of Cyprus's website [12] of year 2005 and solar irradiation data obtained from SODA solar radiation data website [88] of year 2005 are used to create figure 33 and 34. Figure 33 illustrates the relationship between solar radiation versus the air temperature. The temperature curve peaks at around day 224 whereas; solar radiation is at its maximum at around day 176 of year 2005. Therefore, there is a lag or delay of around 48 days between the maximum radiation and maximum temperature. This annual lag of temperature behind radiation is called the "annual march of temperature". It is a result of the changing relationship between incoming solar radiation and outgoing Earth radiation [87]. In this case, temperatures continue to rise for a month or more after the summer solstice because radiation continues to exceed Earth's radiation loss. Temperatures continue to fall after the winter solstice until the increase in radiation finally matches Earth's radiation. Therefore, the lag exists because it takes time for Earth to heat or cool and for those temperature changes to be transferred to the atmosphere.

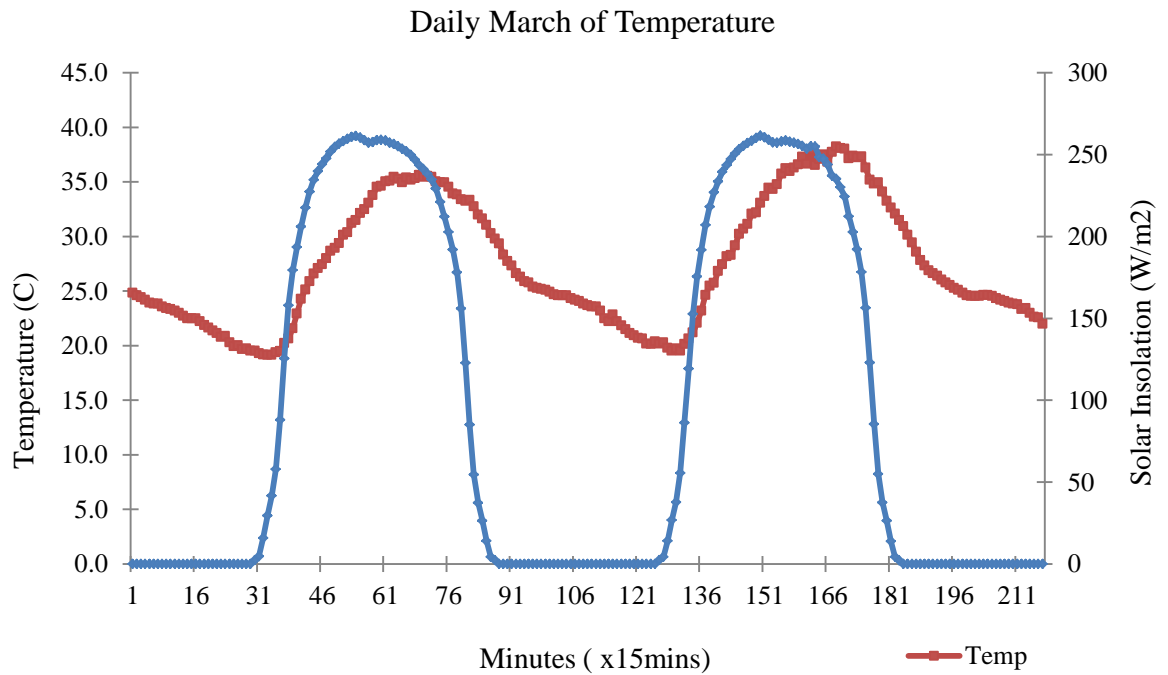


Figure 34: Daily March of Temperature of Cyprus for year 2005 on days 185 and 186 (June)

Each day, radiation receipt begins at sunrise, reaches its maximum at noon and return to zero at sunset. Although radiation is greatest at noon, from figure 34, it is noticeable that the mean temperature does not reach its maximum until 2 pm. This is because the radiation received by Earth from sunrise until the afternoon hours exceeds the energy being lost through Earth radiation. Hence, during that period, as Earth and atmosphere continue to gain energy, temperatures normally show a gradual increase. In the afternoon, when outgoing Earth radiation begins to exceed radiation, temperatures start to fall. The daily lag of Earth radiation and temperature behind radiation is accounted for by the time takes for Earth's surface to be heated to its maximum and for this energy to be radiated to the atmosphere. From figure 34, it is also observed that there is slower decay in temperature once the radiation is declined rapidly. Again, this is due to energy that has been stored in Earth's surface layer during the day which continues to be lost throughout the night and the ability to heat the atmosphere decreases. The lowest temperatures occur around dawn, when the maximum amount of energy has been emitted and before replenishment from the sun can occur. This phenomenon is also known as the daily march of temperature [87]. From figure 34, on this basis the daily march of temperature phenomenon, there is a gentle decline from mid-afternoon until dawn and a rapid increase in the 8 hours or so from dawn until the next maximum is reached.

As a result, the relationship between air temperature and electricity demand and the relationship between air temperature and solar irradiation hence the indirect relationship between solar irradiation and electricity demand has been identified. Therefore, the predictability of solar radiation and its indirect relationship with the electricity demand enables the system or grid operator to predict their peak demand which is cause of the solar radiation in the first place.

On the basis, that electricity demand is linked to air temperature and air temperature is linked to solar radiation, it can be concluded that solar energy is one of the best options that are to be exploited to provide power to the grid system in matching peak demands in Cyprus [194].

5.2. System flexibility and conventional operation

Electric power systems are designed to respond to the aggregated instantaneous electricity demand of a larger number of consumers i.e. domestic, agriculture, industrial etc. Electricity demand is a function of time of day, weather, season, business cycles, TV pickups etc., and there is considerable variation in amount of electricity used and hence its demand patterns. Figure 35 is a typical summer week electrical demand from July 2010 of Northern Cyprus created using the data provided by [13]. The figure is a good example demonstrating different levels and patterns of electricity consumption per each week day. From the figure, it can be observed that Monday demand curve is ramping up from 6 am up to the knee point at 10-11 am then ramps to the peak around 3-4pm. The Monday demand then ramps down until 7-8 pm and picks up once again for a second lower local peak in the evening around 9-10 pm. The Saturday demand starts ramping up similar to Monday demand from 6 am. However, once at the knee point at around 10-11am it remains at peak as a daily plateau until in the afternoon 4-5 pm. Then it has similar evening peak behaviour to the Monday demand. The Sunday demand starts ramping up slightly later in the morning at around 7-8 am. It has a lower ramp up rate up and ramps up until peak afternoon time at around 2-4pm. After the afternoon peak there is a second ramping until the evening peak at around 9-10 pm. In Sunday's demand the daily peak demand appears in the evening compared to other days of the week. This example can be extended to any week of the seasons and that would be a different picture demonstrating complex demand behaviour.

Additional insight into the electricity use and power system operation can be gained by re-ordering the annual demand data into a load duration curve (LDC). A LDC indicates the total number of hours a system is required to provide a given amount of load. Figure 36 provides a LDC for Northern Cyprus of year 2010 created using the data provided by [13].

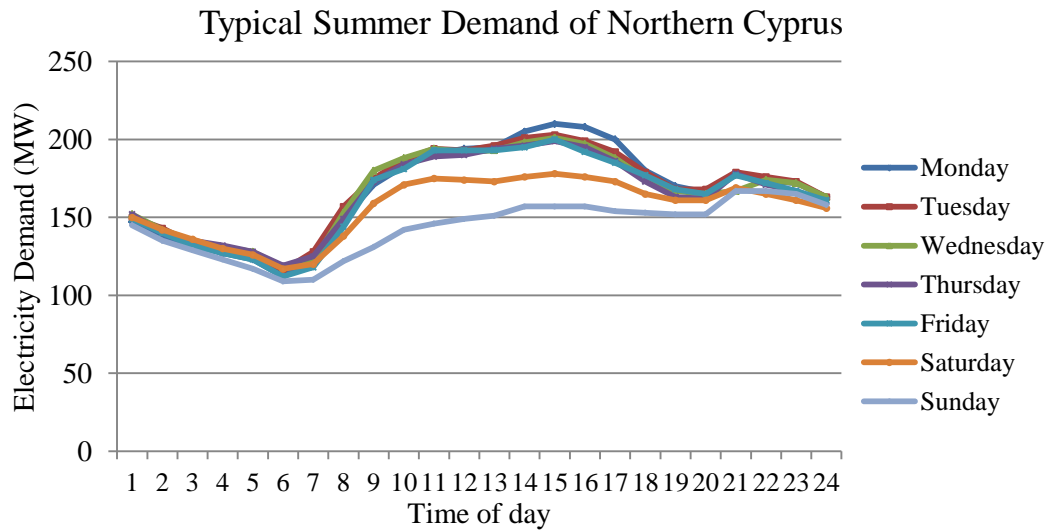


Figure 35: Typical summer demand of Northern Cyprus [13].

For demonstration purposes, there are four loosely defined regions called peak, intermediate, base and hypothetical minimum shown on this curve.

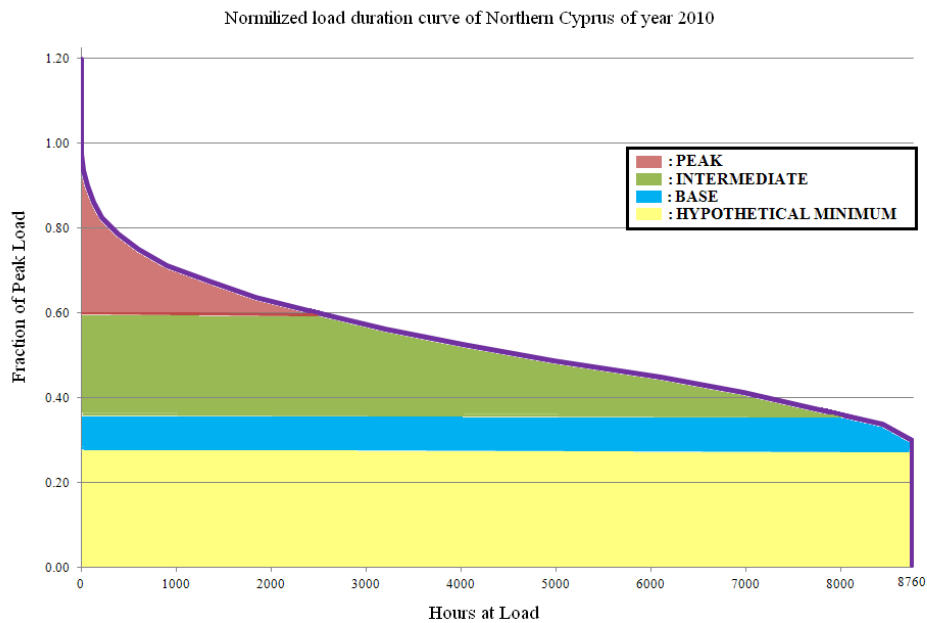


Figure 36: Normalised load duration curve for Northern Cyprus of year 2010.

Control mechanisms have been developed to manage variability and uncertainty and maintain reliable operation because of the electricity demand is constantly changing, making variability and uncertainty inherent characteristics of electric systems.

To understand the need for flexibility in the generation fleet, it is useful to examine the different grid operating timeframes, which can be divided into regulation, load following, and unit commitment. Figure 37 below provides a graphical depiction of the three general timeframes and the control mechanisms applicable to each.

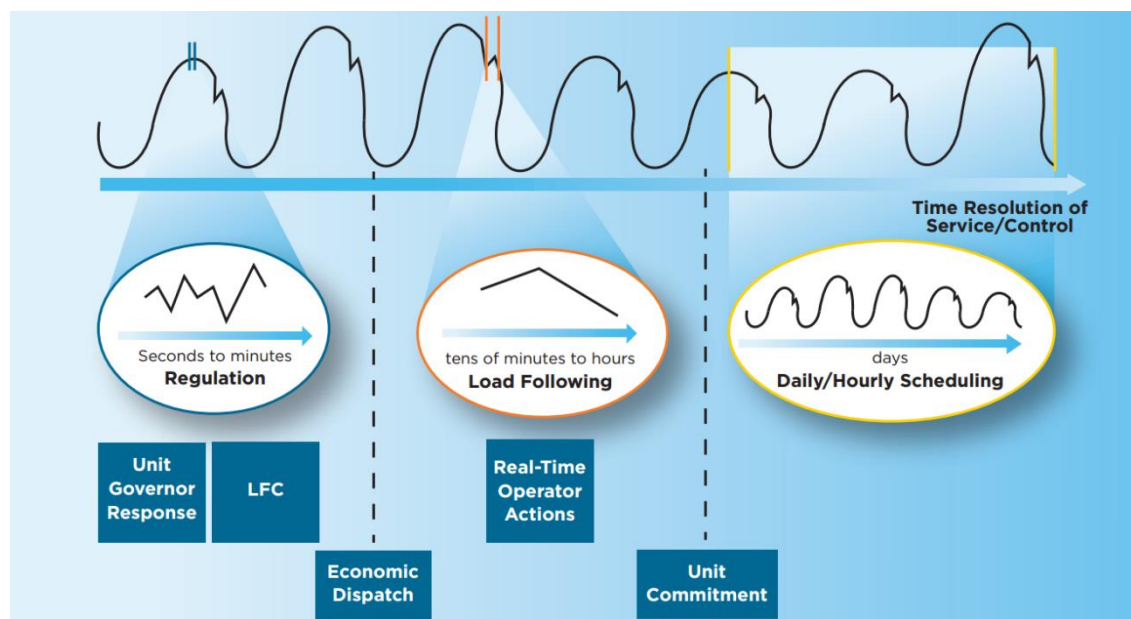


Figure 37: System operating timeframes and control mechanism [90].

Regulation typically ranges from several seconds to 5 minutes, and covers the variability that occurs between subsequent economic dispatches. Using automatic generation control (AGC), generation automatically responds to minute-by-minute load deviations in response to signals from grid operators. Changes in load during the regulation time are typically not predicted or scheduled in advance and must be met through generation that is on-line, grid-synchronized, and under automated control by the grid operator [90].

Load following typically ranges from 5–15 minutes to a few hours. Generating units that have been previously committed, or can be started quickly, can provide this service, subject to operating constraints on the generator [90].

Unit commitment typically covers several hours to several days. Unit commitment involves the starting and synchronizing of thermal generation so that it is available when needed to meet expected electricity demand [90].

Ramp rate is essentially the speed at which a generator can increase (ramp up) or decrease (ramp down) generation. Generating units have different characteristics; making some more suited to supplying certain needed functions [90].

Base load units are typically large nuclear and coal-fired facilities—often supply the same amount of energy around the clock, although many coal units follow the diurnal load cycle, running at minimum generation levels at night and increasing during the day. These units have slow ramp rates and relatively high minimum generation levels, referred to as turn-down capability. They also can take a long time (days in some cases) to start back up once they have been cycled off. Large base load units also tend to have lower operating costs relative to other fossil-fuelled facilities [90].

Intermediate and peaking units, which are generally natural gas or oil-fired facilities, have faster ramp rates, relatively lower minimum generation levels, and can be shut down and started up relatively quickly. However, they also have relatively higher operating costs. Intermediate and peaking units are most often used to provide load following generation service due to their ability to ramp up and down quickly. Hydro generation has fast response, but can be restricted by environmental constraints (such as erosion control, accommodating salmon, etc.), scheduling practice, and market characteristics. In addition to intermediate and peaking units, there are many additional potential sources of flexibility, ranging from advanced thermal generators, institutional factors, demand response, fuel storage, and electricity storage. In general, the desired mix of flexibility is determined by the need to maintain reliability in the most economical way possible [90].

At this point following from the findings of section 4.1, it can be expected that any solar generation (with no storage capacity), should fit into the summertime demand pattern illustrated in figure 35. Highest demand periods occur during the day, with seasonal demand cycle peaking during the summer, which can be correlated with the solar generation output.

However, it is not immediately obvious how solar or other renewable generation in this case interacts with overall demand profile as the RES generation achieves increasing levels of penetration, especially non summer time periods when electricity demand is not driven by air conditioning.

Unlike conventional generators, intermittent sources of electricity can not respond to the variation in normal consumer demand patterns. Rapid fluctuations in output can impose burdens on generators and limit their use. The ability to integrate fluctuating sources is improving, and it is unclear to what extent these short term fluctuations limit the fraction of a system's energy that can be provided by intermittent renewable. There is, however, a somewhat absolute limit to the economic integration of renewable energy sources such as solar PV or wind, based on the fundamental mismatch of supply and demand. Only so much RES generation can be integrated into an electrical power system before the supply of energy exceeds the demand. This problem is exacerbated by conventional power systems, which have limited ability to reduce output of base load generators.

Therefore, more in depth analysis is required to assess the level of RES generation penetration in to the electrical system of Cyprus in the terms of base load supply capacity of conventional generation.

5.3. Factors that constrain the level of penetration for grid connected PV systems

Grid interconnection of PV power generation system has the advantage of more effective utilization of generated power. However, the technical requirements from both the utility power system grid side and the PV system side need to be satisfied to ensure the safety of the PV installer and the reliability of the utility grid. Clarifying the technical requirements for grid interconnection and solving the problems such as islanding detection, harmonic distortion requirements and electromagnetic interference are therefore important issues for widespread application of PV systems [93]. Grid interconnection of PV systems is accomplished through the inverter, which converts dc power generated from PV modules to ac power used for ordinary power supply to electric equipments. Inverter system is therefore important for grid-connected PV systems.

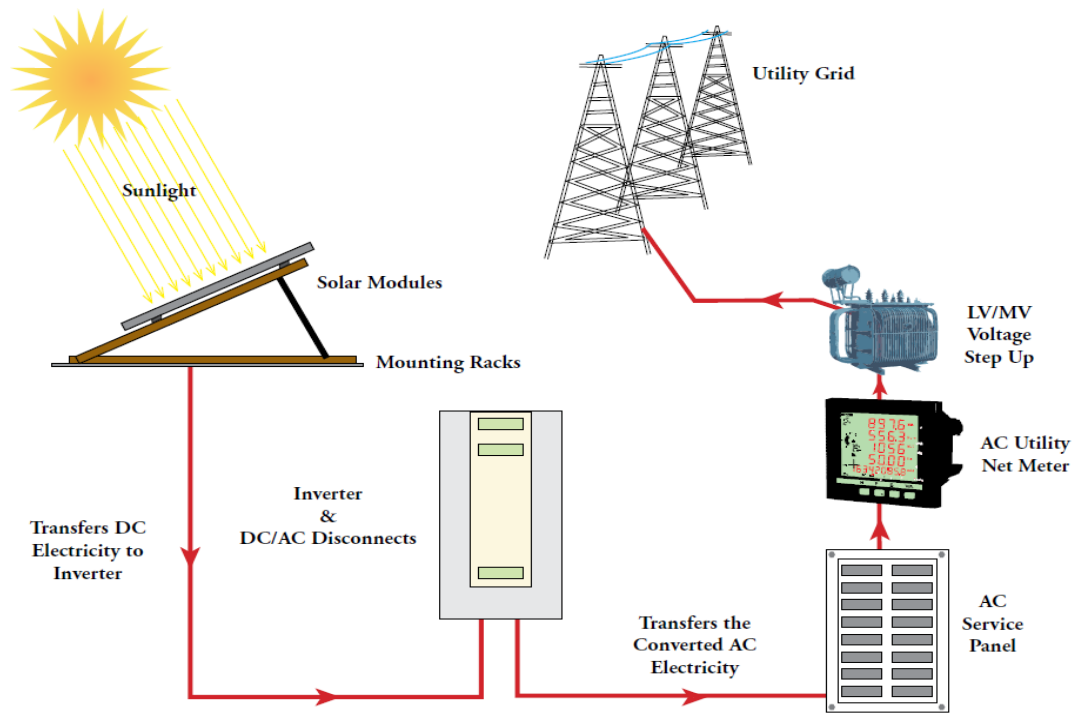


Figure 38: Grid connected power system with no storage

The simplified diagram of a grid connected power system with no storage is shown at figure 38. The inverter may simply fix the voltage at which the array operates, or (more commonly) use a maximum power point tracking function to identify the best operating voltage for the array. The inverter operates in phase with the grid (unity power factor), and is generally delivering as much power as it can to the electric power grid given the available sunlight and temperature conditions. The inverter acts as a current source; it produces a sinusoidal output current but does not act to regulate its terminal voltage in any way [93].

The utility connection can be made by connection to a circuit breaker on a distribution panel or by a service tap between the distribution panel and the utility meter. Either way, the PV generation reduces the power taken from the utility power grid, and may provide a net flow of power into the utility power grid if the interconnection rules permit [93].

An extensive literature search was conducted to collect the available information on expected problems associated with high penetration levels of grid connected PV. The penetration level is defined as the ratio of nameplate PV power rating (W_{peak}) to the maximum load seen on the distribution feeder (W). The results of that literature survey are presented below.

Macedo and Zilles [95] examined cloud transient effects if the PV were deployed as a central-station plant, and it was found that the maximum tolerable system level penetration level of PV was approximately 5%, the limit being imposed by the transient following capabilities (ramp rates) of the conventional generators.

Patapoff and Mattijetz [96] focus on the operating experience of the Southern California Edison central-station PV plant at Hesperia, CA. The report suggested no such problems, but suggests that this plant had a strong connection to the grid and represented a very low PV penetration level at its point of interconnection.

Jewel et al. [97] dealt with voltage regulation issues on the Public Service Company of Oklahoma system during the passage of clouds over an area with high PV penetration levels, if the PV were distributed over a wide area. At penetration levels of 15%, cloud transients were found to cause significant but solvable power swing issues at the system level, and thus 15% was deemed to be the maximum system level penetration level.

A study in paper by Cyganski et al [98] describing the harmonics at the Gardner, MA PV project. The 56 kW of PV at Gardner represented a PV penetration level of 37%, and the inverters (APCC SunSines) were among the first generation of “true sine wave” PWM inverters [99]. All of the PV homes were placed on the end of a single phase of a 13.8 kV feeder. The PV contribution to voltage distortion at Gardner was found to be about 0.2%, which was far less than the contributions made by many customer loads [98]. It was thus concluded that harmonics were not a problem as long as the PV inverters were “well designed”. This paper also mentions the potential value of PV systems being able to provide reactive power to keep the power factor of a feeder approximately constant.

The Gardner, MA PV project [99] looked at four areas: the effect on the system in steady state and during slow transients (including cloud transients); how the concentrated PV responded under fast transients, such as switching events, islanding, faults, and lightning surges; how the concentrated PV affected harmonics on the system; and the “overall performance of distribution systems”, in which the total impact of high-penetration PV was evaluated. The final conclusion is that the 37% penetration of PV at Gardner was achieved with no observable problems in any of the four areas studied.

Jewell and Unruh [100] attempted to quantify the impact of geographic distribution of PV on allowable PV penetration level, at the system level, using a utility in Kansas. The study concluded that under the conditions studied, the utility's load-following capability limited PV penetration to only 1.3% if the PV were in central-station mode, with the limitation being caused by unscheduled tie-line flows that unacceptably harmed the utility's economics. However, the allowable penetration rose to 36% if the PV is scattered over a 1000 km² area, because of the “smoothing” effect of geographic diversity.

Asano et al. [101] studied the impact of high penetrations of PV on grid frequency regulation which responding to synthetically generated short-term irradiance transients due to clouds. The study looked at system frequency regulation, and also at the “break-even cost” which accounts for fuel savings when PV is substituted for peaking or base load generation and the cost of the PV. This study concluded that, the break-even cost of PV is unacceptably high unless PV penetration reaches 10% or so. The thermal generation capacity used for frequency control increases more rapidly than first thought, and that a 2.5% increase in frequency control capacity over the no-PV case is required when PV penetration reaches 10%. For PV penetration of 30%, the authors found that a 10% increase in frequency regulation capacity was required, and that the cost of doing this swamps out any benefit. Based on these two competing considerations, the authors conclude that the upper limit on PV penetration is 10%.

The International Energy Agency (IEA) has produced a series of reports on Task V of the PV power systems (PVPS) implementing agreement. Islanding, capacity value, certification requirements, and demonstration project results were all the subject of investigations, but the one that is of primary importance here dealt with the subject of voltage rise [102]. This report focused on three configurations of high-penetration PV in the low-voltage distribution network (all PV on one feeder, PV distributed among all feeders on an MV/LV transformer, and PV on all MV/LV transformers on an MV ring). This study concludes that the maximum PV penetration will be equal to whatever the minimum load is on that specific feeder. That minimum load was assumed to be 25% of the maximum load on the feeder in [102], and if the PV penetration were 25% of the maximum load, then only insignificant over voltages occurred. Any higher PV penetration level increased the over voltages at minimum loading conditions to an unacceptable level.

Two major studies by NREL [103] and [104] concentrated on distributed generators interfaced to utilities through inverters, and larger-scale system impacts and rotating distributed generation (DG), but still with several results on inverter-based DG. The first study [103] concluded that for DG penetration levels of 40%, such that the system is heavily dependent on DGs to satisfy loads, voltage regulation can become a serious problem. The sudden loss of DGs, particularly as a result of false tripping during voltage or frequency events, can lead to unacceptably low voltages in portions of the system. During periods of low load but high generation and with certain distribution circuit configurations, the reverse power flow condition could cause malfunctions of the series voltage regulators. Again, voltage regulation becomes a problem.

A voltage regulation function, implemented through reactive power control, would enable inverter-based DGs to be much more beneficial to the grid than they currently are. Unfortunately, this function would interfere with most anti-islanding schemes as they are presently implemented. Inverter-based DGs do not contribute significantly to fault currents, and thus did not adversely impact coordination strategies for fuses and circuit breakers.

The study notes that the short-duration fault current contribution of small distributed inverter-based DGs is smaller than that of distributed induction machines. However, it also points out that this might not always be true if the DG is connected at a point where the utility series impedance is unusually high. These conclusions may not remain valid if the voltage regulation controls suggested above are implemented.

The inverter-based DGs did not respond adversely to high-speed transients such as those caused by capacitor switching, and thus did not degrade the system's response in such cases. For widely dispersed DGs, modern positive feedback-based anti-islanding appears to be effective in eliminating islands without causing serious impacts on system transient performance, but the complexity of the subject indicates that more study is needed.

Significant impacts were observed when DG penetration levels were between 10 and 20% [105]. This study suggests that active anti-islanding, particularly involving positive feedback on frequency has a negative but minor impact on system dynamic behaviour.

Another report in 2006 was produced by a European consortium called distributed generation with high penetration of renewable energy sources (DISPOWER) that includes Universities, research institutes, manufacturers, and representatives of several segments of the utility community [107]. This report examined many different types of DG in many configurations. Items in the DISPOWER report that are of specific interest here include the following. The report describes a Power Quality Management System (PQMS), which uses TCP/IP as its protocol and Ethernet cables as the physical communications channel. Initial field tests appear to be promising. One section of the report deals specifically with problems expected as DGs approach high penetration levels. The authors studied both radial and mesh/loop distribution system configurations and concluded that the mesh/loop configuration has significant advantages for mitigating the problems associated with high DG penetration. They also pointed out that harmonics increased slightly when the DGs were present, but they did not reach a problematic level. This study does not include a suggestion of a maximum penetration level.

Furthermore, Dispower [106] examined the impact of DGs on distribution system losses, as a function of penetration level and DG technology. It concluded that distribution system losses reach a minimum value at DG penetration levels of approximately 5%. But the distribution system losses begin to increase as penetration increases above that level. The reasons for this are not clear, but the general result that there was a penetration level at which distribution losses were minimized was consistent across all DG technologies. The penetration level at which minimum losses occurred was nearly doubled if voltage regulating, variable power factor inverters were used.

A recent study by the European Network of Transmission System Operations for Electricity [108] examined the impact of PV penetration in the UK, where utility source series impedances are typically higher than in the U.S. It examined the probability distributions of voltages in a simulated 11 kV distribution system with varying levels of PV penetration, using an unbalanced load flow model. PV output was simulated using measured data with 1-min resolution. The probability density functions indicated that PV causes the distribution to shift toward higher voltages, but only by a small amount. Mean point of common coupling voltages increased by less than 2 V (on a 230-V nominal base).

The study's findings include the following: If one employs very strict reading of the applicable standard in the UK (BS EN 50160), then PV penetration is limited to approximately 33% by voltage rise issues. However, at 50% penetration, the voltage rise above the allowed limits was small, and so the authors suggest that the 33% limit is somewhat arbitrary. Reverse power flows at the sub-transmission-to-distribution substation did not occur even at 50% PV penetration.

Contrary to the results in [105], Thomson and Infield [107] found that at 50% penetration distribution system losses were reduced below the base-case values, largely because of reductions in transformer loading. Voltage dips due to cloud transients might be an issue at 50% penetration, and the authors suggest further study of this issue.

The maximum PV penetration levels suggested in different literatures are summarized in figure 39.

Considering that Cyprus's has been set with very ambitious targets regarding the penetration of renewable power generation, it can be anticipated that the implementation of multi-megawatt RES generation may cause some problems regarding the system operation.

For example, large-scale integration of multi-megawatt solar plants, especially utility scale PV plants, into grid operation would therefore lead to new operation constraints i.e. power is produced during the day, when the electricity demand is high, thus it is valuable peak current, for the entire HV distribution & transmission system, that could result inadequate in the next years in terms of system performance (grid and generating plant).

Max PV penetration level	Cause of the upper limit	Ref. No
5%	Ramp rates of main-line generators. PV in central-station mode.	[69]
15%	Reverse power swings during cloud transients. PV in distributed mode.	[71]
No limit found	Harmonics.	[72]
>37%	No problems due to clouds, harmonics or unacceptable responses to fast transients were found at 37% penetration. Experimental + theoretical study.	[73]
Varied from 1.3 to 36%	Unacceptable unscheduled tie-line flows. The variation is caused by the geographical extent of the PV (1.3% for central-station PV). Results particular to the studied utility because of the specific mix of thermal generation technologies in use.	[74]
10%	Frequency control vs. breakeven costs	[75]
Min Load	Voltage rise. Assumes no load tap changing's in the MV/LV transformer banks. Max penetration level is equal to the minimum load on feeder	[76]
<40%	Primarily voltage regulation, especially unacceptably low voltages during false trips and malfunctions of series voltage regulators.	[77] and [78]
5%	This is the level at which minimum distribution system losses occurred. Note that this level could be nearly doubled if inverters were equipped with voltage regulation capability.	[79]
33% or >50%	Voltage rise. The lower penetration limit of 33% is imposed by a very strict reading of the voltage limits in the applicable standard but the excursion beyond that voltage limit at 50% penetration was extremely small.	[81]

Figure 39: Summary of maximum PV penetration levels suggested in the literature

5.4. The grid code requirements for solar technologies

In the last couple of years, some new Directives and new Grid-Codes have been released by national authorities and by Transmission System Operators; such guidelines are not harmonized and therefore inhomogeneous requirements are still required at national level (most probably due to the local Grid situation). In this respect, new initiation since 2012 has been in place among the European countries. This initiation is called European network of transmission system operators for electricity (ENTSO-E). Secondment from Europe's Transmission System Operators (TSOs), ENTSO-E is delivering European-wide network codes, technical reports, market developments and is at the forefront of EU policy issues related to electricity transmission systems and market operations. ENTSO-E is working and collaborating with EU institutions, governments, regulators and power system stakeholders. Currently 41 TSOs from 34 countries are members of ENTSO-E [108].

Since the island Cyprus has no interconnections to any other country, South Cyprus's TSO, EAC is one of the members under the voluntary regional group isolated systems (RG IS) [108].

While in the past, renewable generating units connected to the network were commonly not required to take over an active role and had to “disconnect at the first sign of trouble”, the new guidelines now require also the renewable generating units to actively support the grid during normal as well as disturbed conditions. This step is being regarded more and more as absolutely necessary to guarantee reliability and quality of supply in the mid- to long-term. This new approach has already been adopted in Germany and France and is being adopted also in Cyprus in the following years [91].

Although the new Directives and new Grid Codes introduced specific requirements for wind and solar generating plants, CSP plants are not specifically mentioned. It is unclear whether they should be treated as renewable generating units or should be considered, especially the Parabolic Trough technology, in all respects as conventional generating units (due to behaviour of power block which is used to generate electrical power from the solar field) and therefore have to comply with the relevant specific requirements.

The penetration of renewable energies in the power grids has been increasing in the last couple of years due to successful regulations which have been implemented by the European Countries. One of the leader countries in respect to implementing PV systems is Germany. To prevent grid instability due to a high penetration of renewable energies a German directive for connecting generating plants to the grid has been released [109].

Main and mandatory requirements introduced by the this directive were;

- a) Active power control
- b) Automatic frequency response
- c) Reactive power control
- d) Fault ride through capabilities

5.4.1. Active power control

To avoid possible network congestion in case of line loss due to an electrical fault any renewable generating unit, such as Utility-Scale PV plant or and CSP plant, shall be able to reduce its power. Therefore the TSO is in the position to require curtailment of the power output of solar power plants to face with the specific critical system conditions. Different requirements may be applied for the CSP plants rather than the Utility Scale PV plants because the CSP looks like a conventional generating plant using rotating synchronous generating unit, while PV is using a static inverter.

Power output of PV generating plants has to be reduced in steps of 10% per minute, under any operating condition and from any working point to a maximum power value (target value) which could correspond also to 100% power reduction, without disconnection of the plant from the network [110].

Such requirement might be applied also to CSP plants if they are considered in all respect as renewable generating units, otherwise they have to fulfil requirements set for the conventional generating units, which are required to reduce – or to increase - their output with different ramp-rate between the minimum stable generation power and the continuous output.

CSP plants may fulfil the requirement set for the PV generating units provided that the set-point given by TSO is compatible with the minimum operating load of the boiler and steam turbine. Since the characteristics of the CSP plant are similar to the traditional thermal power plant, the load reduction can reach values around 40% of the nominal capacity, with limiting factor the stable operation of the heat exchangers. The advantage of CSP is that, in case of temporary reduction (limited to few hours), the solar energy captured by solar field is not be lost because it could be stored in the thermal storage system (of course it depends on specific storage capacity, by the actual operating condition, by sun condition, etc).

Also for the Utility Scale PV plants such requirement do not constitute an issue provided that an automatic power sharing management system is installed and it is capable to modulate the production of the entire plant, by acting on each inverter, through a communication based solution, by sending new power output set points or by sending shut down command to disconnect several inverters, or again, by combining the two controls. Of course if battery storage system is not installed, the amount of reduced power is definitely lost.

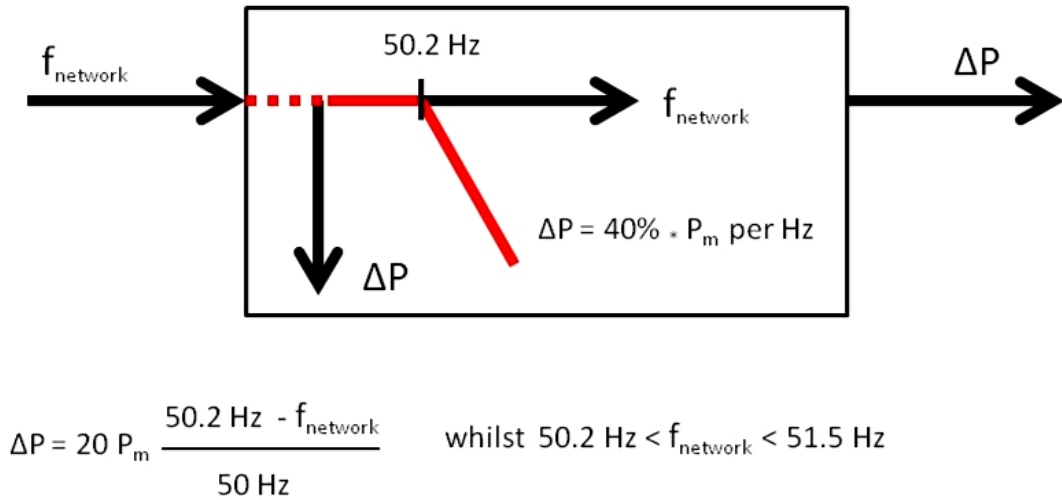
So from technical point of view there are no barriers that may prevent CSP and utility Scale PV plants to be compliant with such specific Grid-Code requirements. A cost increase may be envisaged for the PV plants (rather than CSP plants) to implement the power sharing management system [111].

5.4.2. Automatic Frequency Response

To avoid risk of unsafe system operation when the frequency rise over a certain value, any renewable generating unit, such as Utility-Scale PV plant or and CSP plant, shall have the capability to reduce its power generation when the grid frequency exceeds a pre-set value.

Reference value for the active power reduction ΔP would be relatively larger percentage of the currently available power generation value at the point in time when the grid frequency is equal to 50.2Hz. This active power reference value must be reduced according to a coefficient of some output percentage per Hz when the grid frequency deviates from the pre-set value. The German Transmission Code requires, for all the renewable-based generating units, to reduce the active power with a gradient of 40% of the plant's

instantaneously available capacity per Hz as shows in the below figure 40. Requirements, in terms of power output adjustment and time duration, may be different country by country and mainly depends by local network conditions [112].



P_m : instantaneously available power
 ΔP : power reduction
 f_{network} : network frequency

Figure 40: Active power reduction of generating units in the case of over frequency [112].

Furthermore the generating units have to remain connected to the grid (without tripping) if either the grid frequency increases to values equal to 51.5Hz or decreases to values equal to 47.5Hz; above 51.5Hz and below 47.5Hz the plants can be disconnected [112].

These requirements can fairly easily be fulfilled by the Utility scale PV system. A new control scheme has to be included in each inverter to control the operation point of the PV string and thus the power output. The inverter will automatically reduce the power output and stays constant until frequency is decreased below the pre-set value and after will increase automatically the power output switching to MPP (maximum power point) tracking control.

CSP plants can easily fulfil such requirements and additionally could provide, since they can be considered in all respect as conventional generating units, the primary frequency control, provided that the whole plant controls (steam turbine, steam exchangers and thermal storage) is capable to operate in droop mode and with the required ramp rate. This coordinated regulation requires the simultaneous reaction of steam turbine control system (that acts on the inlet steam control valves) and of steam exchangers control system (that acts on feed-water flow and hot fluid flow) to meet the fast response and wide variations required by the frequency control. CSP plant may also provide ancillary services, such as secondary frequency control and minute reserve, by means of appropriate thermal storage system [111].

5.4.3. Reactive power control

Slow changes in network voltage have to be kept within acceptable limits. In case of operation requirements and on demand of the system operator, any renewable generating unit, such as Utility-Scale PV plant or and CSP plant, has to support network voltage by injecting on the Grid appropriate amount of reactive power, in accordance with Network operator request.

Utility-scale PV plants installed today are designed to produce active power only. Reactive power is avoided due to losses in the inverter, lines and transformers. To meet the requirements of the grid codes, the inverters of the Utility-Scale PV plant have to be designed to be larger or to use a centralized static VAR compensation system have to be installed. Reactive power has only to be provided during feed-in operation, so there is no need to provide reactive power during the night. Overall, an increase of PV installation system costs can be expected [111].

CSP plants can fulfil the minimum power factor and/or the reactive power control because their generating units use by synchronous generators equipped with excitation system capable to provide reactive power as required. Therefore the amount of reactive power that can be delivered to the Grid mainly depends by size of generator and relevant excitation system as for the conventional generating units.

In addition, CSP plants may be requested to provide different amount of reactive power during different voltage situations since could be considered in all respect as conventional generating units. Apart from the requirements to provide reactive power supply in the nominal design point of the generating unit ($P=P_n$), there would be also requirements concerning operation at an active power output below the nominal active power ($P<P_n$). In this case, CSP plant may be requested to operate its generator in every possible working point in accordance with the generator output diagram. The relevant request can arise according to the situation on the network and imply that the provision of reactive power takes precedence over the supply of active power.

5.4.4. Fault ride through capability

The Code distinguishes the renewable generating units in two different categories: the ones based on synchronous generators and all the other generating units. Both the categories are required to contribute, according to their capability, with different kind of dynamic support. Since the CSP could be considered in all respects as conventional generating units, they should meet requirement set for the conventional generating units, while all the other renewable generating units, such as PV system, have to meet specific requirements as described below.

In the event of network fault, with consequent voltage drop, any PV plant has to remain connected to the grid and to inject a certain amount of short-circuit current (agreed case-by case with the network Operator) into the network; furthermore it shall feed-in the same active power (and to absorb the same or less reactive power) as soon as the fault is cleared.

The Code specifies the voltage drop that shall be ride and through by any PV generating plant (Voltage through capability) as shown in the figure 41. On the diagram, above “borderline 1” indicates that the generating units must be remained connected, above “borderline 2” and below “borderline 1” indicates that generating units have to remain connected even if not capable to support voltage network. Below the “borderline 2”, the generating units are allowed to be disconnected.

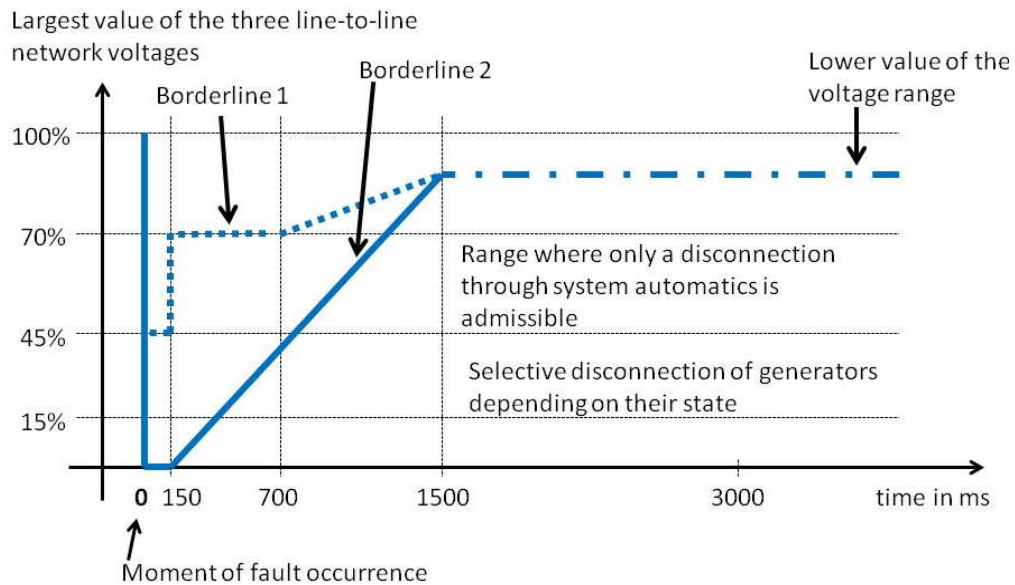


Figure 41: Limiting curves of voltage at the Grid connection point in the event of network fault [111]

As shown in the next figure 42, different “fault-ride through” capability requirements are specified by different Grid Codes within European countries [112]. The “fault-ride through” capability curves are quite similar, but the dynamic requirements are different, mainly with respect to voltage support during the voltage drop.

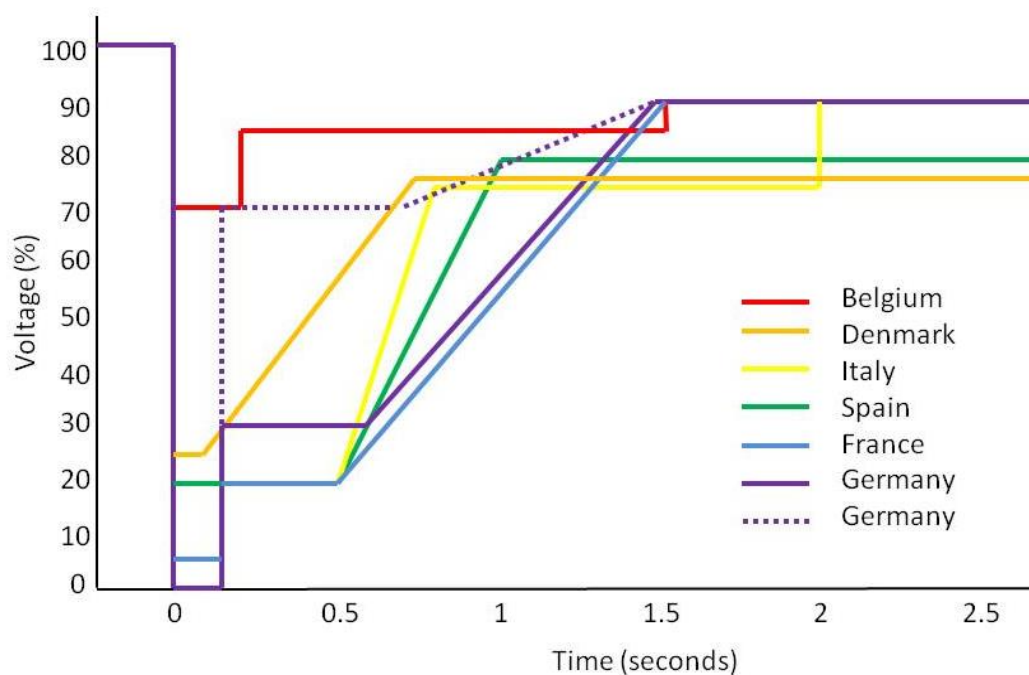


Figure 42: Comparison of “fault-ride through” capability required by different Grid Code in the event of network fault

The German Transmission Code requires that PV generating plants have to support the network voltage by injecting additional reactive current during the voltage drop. An appropriate voltage control strategy, as shown in the figure 43, has to be ensured by the PV generating units control system and shall be activated in the event of a voltage drop of more than 10% of the effective value of the generator voltage. This voltage control must ensure the supply of a reactive current at the low voltage side of the generator transformer (i.e. at inverter output terminals) with a contribution of at least 2% of the rated current per percent of the voltage drop. PV generating units must be capable of feeding the required reactive current within 20 ms into the network. If required, it must be possible to supply reactive current of at least 100% of the rated current.

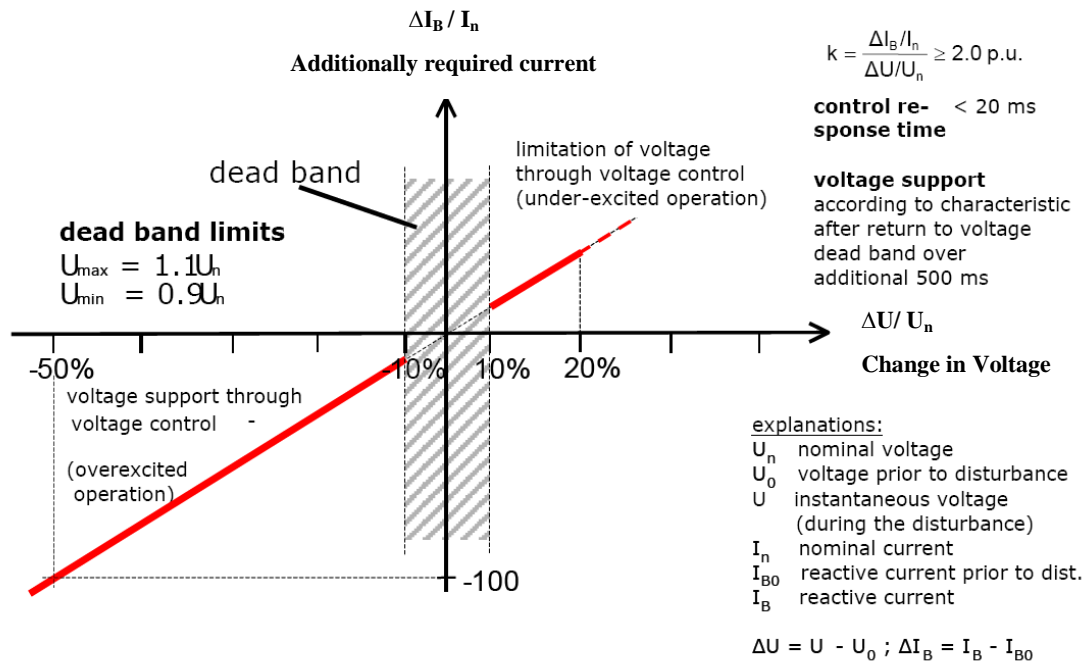


Figure 43: Principle of voltage support in the event of network faults [111]

These requirements do not influence the dimensioning of the PV inverter, but have an impact on control algorithm.

With respect to CSP generating plants, they can be considered as conventional generating units, especially those based on Parabolic Trough technology; therefore the voltage support during voltage drop can be easily achieved by properly designing the generator and the excitation system.

5.5. Grid connected Wind RES and grid operation

It is very important to take the variability of wind into account in a right way in power system studies. The variability will smooth out to some extent if there is geo-spread wind power, and part of the variability can be forecast. Because of spatial variations of wind from turbine to turbine in a wind power plant and to a greater degree from wind power plant to wind power plant, a sudden loss of all wind power on a system simultaneously due to a loss of wind is not a credible event. And also, sudden loss of large amounts of wind power due to voltage dips in the grid can be prevented by requiring fault-ride-through from the turbines.

The variability of wind has been widely studied. Measured large scale wind power production data is available to give insight on the variability that is relevant for power system operation. Figure 44 is a hypothetical graph created showing the measured demand on year 2010 of Northern Cyprus [13] against the actual wind profile of the same year with a hypothetical wind farm with capacity of 100MW. The graph only shows 250 hours of data from mid June 2010. The hypothetical wind farm used is assumed to be consisting of 50 Vestas V90 2.0MW turbines as have been used at the very first wind farm in South Cyprus, Orites sites. This wind turbine has cut in speed at 4 m/s, rated at 12 m/s and cut off at 25 m/s and rated at 2MW [113].

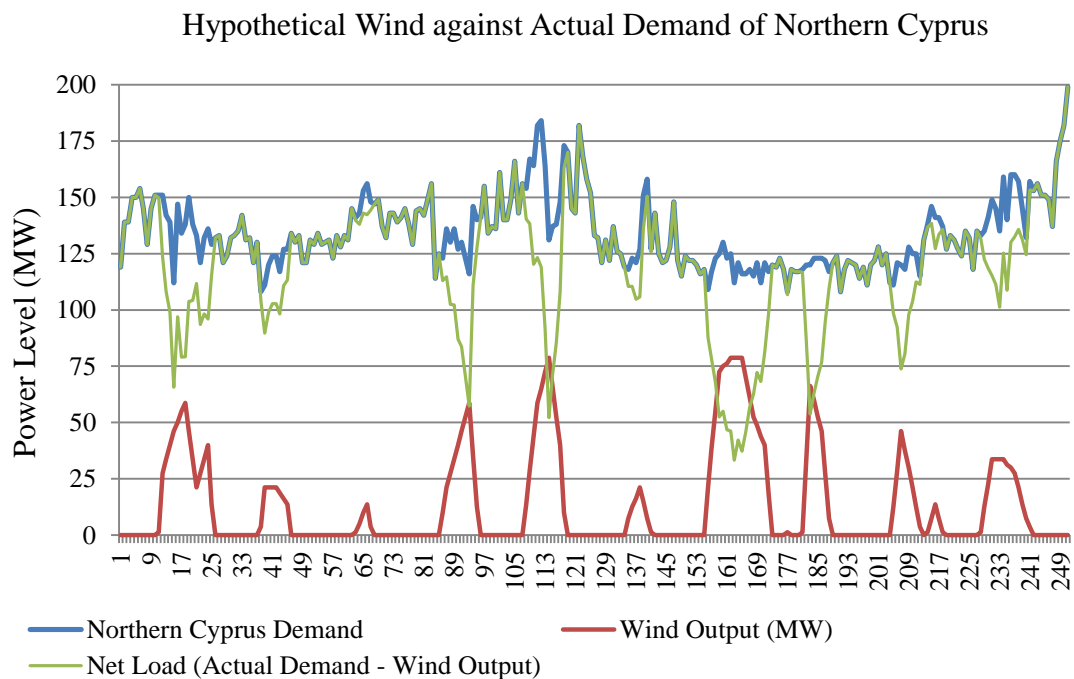


Figure 44: Hypothetical wind power production against actual demand of Northern Cyprus

In-depth information about the variability of wind can be found in [114, 115, 116, 117, 118 and 119]. Generally, the variability of wind decreases as there are more turbines and wind power plants distributed over the area. Larger areas also decrease the number of hours of zero output one wind power plant can have zero output for more than 1000 hours during a year, whereas the output of aggregated wind power in a very large area is always above 0. The variability also decreases as the time scale decreases the second and minute variability of large scale wind power is generally small, whereas the variability over several hours can be large even for distributed wind power. For time scales from several hours to day-ahead, forecasting of wind power production is crucial. Even if some general conclusions can be drawn from the variability of large-scale wind power, however, it should be noted that the size of the area and the way wind power plants are distributed is crucial. Also the landscape can have influence. Offshore, the wind resource has been found to be more coherent, thus increasing the variability compared to similarly distributed wind power onshore.

5.6. Long and short term variability of the wind

There are various factors that cause the intermittent nature of wind generation. These are directly related to the characteristics of the wind resource. As the fuel for wind-generated electricity, the strength, presence, absence and variability of the wind determines not only how much electricity can be generated, but also how reliably the electricity from the wind will be in meeting electricity demand patterns [151].

The factors below directly cause the variability of wind resources [152]:

1. Meteorological conditions
2. Daily/seasonal variations of wind speed (monthly, diurnal)
3. Specific site and height
4. Geographic dispersion of wind plant

The fluctuations in wind speed are dependent on different meteorological conditions. This means that wind resources vary between locations and countries, therefore, each country's wind characteristics should be analysed differently [152].

Besides, wind speed variations may follow a generally daily or seasonal pattern with inter-annual variability. For example, wind speed in the UK vary from summer and winter months as well as contain the element of diurnal variability where wind resource shows a clear pattern of higher wind power output during daylight hours in comparison to overnight [152].

Besides the diurnal, seasonal and inter-annual variations, wind speed at a specific site dictates the amount of energy that can be extracted from the wind technology characteristics. The availability of wind generation depends on the wind speed at the specific location where the wind generators are installed as well as the height of the installation as wind speed varies with height from ground [152].

Geographic dispersion of the wind plant will also affect the variability of wind power output. The variability of wind is not a fixed property, as different geographic locations will experience different wind conditions at any given time. Therefore, it is advantageous to locate wind turbines in a range of locations, rather than being concentrated in one place [152].

The contribution of variable-output wind power to the power system's security, "the capacity credit" of wind, is estimated by determining the capacity of conventional plants displaced by wind power. Alternatively, it is estimated by determining the additional load that the system can carry when wind power is added, maintaining the same reliability level as with the previous conventional generation [152].

Depending on the penetration of a power system with variable wind energy, additional indirect costs arise for maintaining system reliability to supply the varying demand, because wind energy will not be able to meet demand at its average capacity factor, but at a generally reduced rate depending on its capacity credit [153].

In addition, the presence of wind power in a power supply system introduces short-term variability and uncertainty, and therefore requires balancing reserve scheduling and unit commitment. Grid operators need to meet peak demand to certain statistical reliability standards even when wind output falls relative to load. During these periods, which range from minutes to hours, electricity markets need to use demand-following units (such as gas, hydro, or storage), which at times of sufficient wind remain idle, so that costs arise

essentially for two redundant systems [155], and for inefficient fuel use during frequent ramping [154, 155, 156].

Thus, wind energy reduces dependence on fuel inputs, but does not eliminate the dependence on short-term balancing capacity and long-term reliable load-carrying capacity.

The impact of wind power on the power supply system is critically dependent on the technology mix in the remainder of the system, because the more flexible and load-following technology, the less peak reserves are needed. It is also dependent on time characteristics of system procedures (frequency of forecasts etc) and local market rules [157]. In general, the higher the wind penetration, the higher the variability in the supply system, and the more long-term reserve and short-term balancing capacity has to be committed. The corresponding cost increases are only partly offset by a smoothing out of wind variability when many turbines are dispersed and interconnected over a wide geographical area [158], but they are more than offset by reduced fuel and operating costs.

In specific applications, the cost of additional wind power also depends on the relative locations of turbines, load, and existing transmission lines, and on whether sufficient load-carrying reserve exists in the grid or has to be built. As expected, variability costs scatter significantly depending on a large array of parameters. They cannot be derived from capacity credit estimates, since these do not contain any information about to what extent cheap base load and expensive peak load are being displaced by wind [159].

On the other hand maintenance outages of wind turbines are not as problematic with wind power as they are with fossil, nuclear or large hydro, because numerous wind plants are usually distributed over a wide geographical area [160]. Such decentralization in a power supply system reduces the requirements for contingency reserve, since this type of reserve is mostly tied to the largest potential source of failure that is the largest single generator in the system [161].

For grid integration purposes, the short-term variability of wind power (from minutes to several hours) is the most important. It affects the scheduling of generation units, and balancing power and the determination of reserves needed. The short-term variability of wind power, as experienced in the power system, is determined by short-term wind

variations (weather patterns), and the geographical spread of wind power plants. The total variability experienced in the power system is determined by simultaneous variations in loads for all wind power plants and other generation units. The impact of the short-term variation of wind power on a power system depends on the amount of wind power capacity and on many factors specific to the power system in question (generation mix, degree of interconnection), as well as how effectively it is operated to handle the additional variability (use of forecasting, balancing strategy).

The fast variations (seconds to one minute) of aggregated wind power output as a consequence of turbulence or transient events are quite small as can be seen in the operational data of wind farms. As a result they are hardly felt by the system [121].

On the other hand, variations within the hour are felt by the system at larger penetration levels. These variations (10-30 minutes) are not easy to predict, but they even out to a great extent with geographic dispersion of wind plants. Generally they remain within $\pm 10\%$ of installed wind power capacity for geographically distributed wind farms [121].

The most significant variations in power output are related to wind speed variations in the range of 25 – 75% of rated power, where the slope of the power curve is the steepest. The variations within an hour are significant for the power system and will influence balancing capacities when their magnitude becomes comparable to variations in demand; in general this will be from wind energy penetration levels of 5 to 10% upwards [121].

Whereas, variations in hourly timescale are predictable, but cause large amounts of uncertainty, hourly, four-hourly and 12-hourly variations can mostly be predicted and so can be taken into account when scheduling power units to match the demand. In this time scale it is the uncertainty of the forecasts (predicted forecast error) that causes balancing needs, not the predicted variability itself. The system operator always considers the uncertainty of wind power predictions in relation to the errors in demand forecasts and other plant outages [121].

The extent of hourly variations of wind power and demand are shown in figure 45. It is useful to express these wind power variations as a percentage of installed wind power capacity. Extensive studies have been done in many countries and an overview of the conclusions is given in figure 45 [120, 121].

Region	Region Size (km ²)	Number of Sites	10-15 mins		1 hour		4 hours		12 hours	
			Max	Min	Max	Min	Max	Min	Max	Min
West Denmark	40000	>100			-26%	20%	-70%	57%	-74%	84%
East Denmark	40000	>100			-25%	36%	-65%	72%	-74%	72%
Ireland	134400	11	-12%	12%	-30%	30%	-50%	50%	-70%	70%
Portugal	240000	29	-12%	12%	-16%	13%	-34%	23%	-52%	43%
Germany	160000	>100	-6%	6%	-17%	12%	-40%	27%		
Finland	360000	30			-16%	16%	-41%	40%	-66%	59%
Sweden	360000	56			-17%	19%	-40%	40%		

Figure 45: Extreme short term variations of large scale regional wind power, as percent of installed wind power capacity, for different timescales.

In order to investigate benefits of aggregation from geographically dispersed sites, extensive studies have been conducted [120, 121]. As a result, geographical spread of wind power plants across a power system is a highly effective way to deal with the issue of short term variability. Put another way, the more wind power plants in operation, the less impact from variability on system operation.

In addition to helping reduce fluctuations, the effect of geographically aggregating wind power plant output is an increased amount of firm wind power capacity in the system. In simple terms, the wind always blows somewhere. Furthermore, the wind never blows very hard everywhere at the same time. Wind power production peaks are reduced when looking at a larger area, which is important since absorbing power surges from wind plants is challenging for the system. The effect increases with the size of the area considered.

In order to demonstrate the variability of the wind profile of Cyprus, the distribution of hourly, 4-hourly and 12-hourly wind output power plant at Larnaca site, Cyprus is created from the yearly data of 2010. The figure 46 is the illustration of the results.

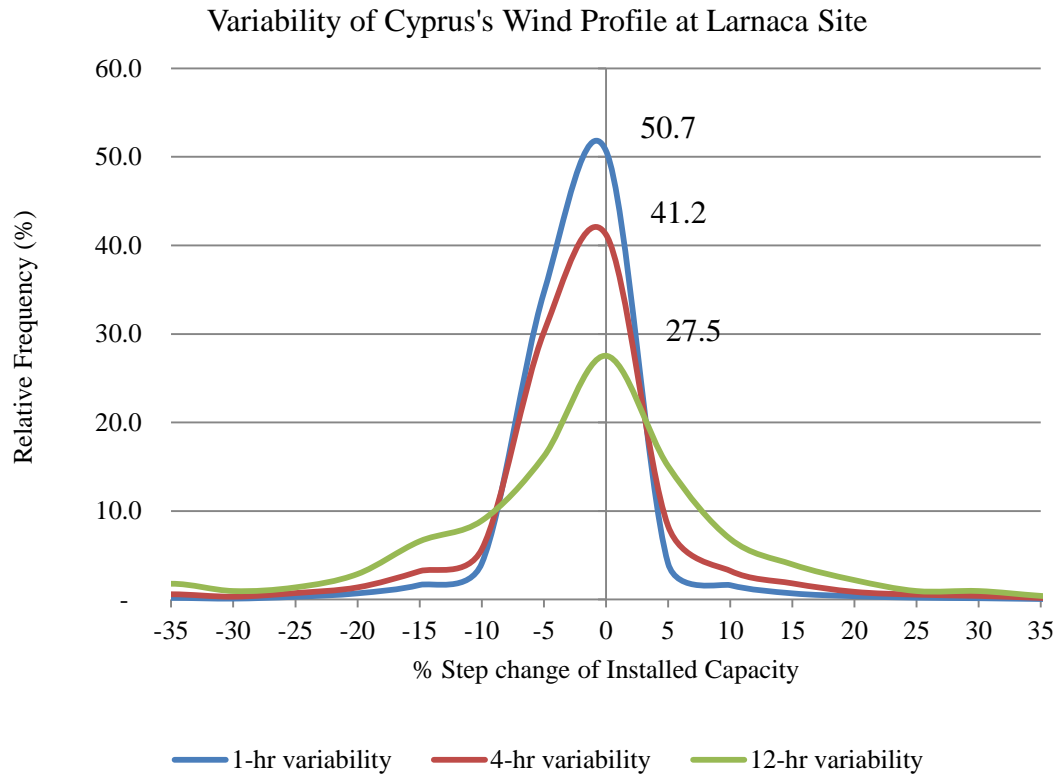


Figure 46: Distribution of hourly, 4-hourly and 12-hourly output of wind power plant at Larnaca site, Cyprus

From figure 46, it can be observed that most of the step changes of the wind generation output will be in the range of -10 to +10 percent of the installed capacity within 1 hour period. This statement is also similar to the 4-hour period. For 12-hour periods, on the other hand, it can be observed most of the variation is in the -5% to +5% window. However, there will be occasions (<10% of the relative frequency) that the variations can go up to -15% to +15% percent of the installed capacity.

5.7. Possible power system impacts of wind power

If the electricity system fails, the consequences are far-reaching and costly. Therefore, power system reliability has to be kept at a very high level. Wind power has impacts on power system reliability and efficiency. These impacts can be either positive or negative. Different time scales usually mean different models (and data) must be used in impact assessment studies. These studies for the system wide impacts can thus fall into the focus areas given by the following subsections.

5.7.1. System stability

Impacted timescale is seconds to minutes. Different wind turbine types have different control characteristics and consequently also different possibilities to support the system in normal and system fault situations. More specifically this is related to voltage and power control and to fault ride through capability. The siting of wind power plants relative to load centres will have some influence on this issue as well. For system stability reasons, operation and control properties similar to central power plants are required for wind plants at some stage depending on penetration and power system robustness. System stability studies with different wind turbine technologies are needed in order to test and develop advanced control strategies and possible use of new components (e.g. FACTS) at wind plants or nearby busbars [120, 121].

5.7.2. Regulation and load following

Impacted time-scale is minutes to half an hour. This is about how the variability and uncertainty introduced by wind power will affect the allocation and use of reserves in the system. Prediction errors of large area wind power should be combined with any other prediction errors the power system experiences, like prediction errors in load. General conclusions on the increase in balancing requirements will depend on region size relevant for balancing, initial load variations and how concentrated or well distributed wind power is sited, as well as the type of terrain topography and local wind structure and typical behaviour. The costs will depend on the marginal costs for providing balancing services or mitigation methods used in the power system for dealing with increased variability and uncertainty. Market rules will also have an impact, as technical costs can be different from market costs [120, 121].

5.7.3. Efficiency and unit commitment

Impacted timescale is hours to days. This impact is due to production variability and prediction errors of wind power. Here the interest is on how the conventional capacity is run and how the variations and prediction errors of wind power change the unit commitment: both the time of operation and the way the units are operated (ramp rates, partial operation, starts/stops). Analyzing and developing methods of incorporating wind power into existing planning tools is important, to take into account wind power uncertainties and existing flexibilities in the system correctly. The simulation results give insight into the technical impacts of wind power, and also the (technical) costs involved. In

electricity markets, prediction errors of wind energy can result in high imbalance costs. Analyses on how current market mechanisms affect wind power producers are also important [120, 121].

5.7.4. Transmission adequacy and efficiency

Impacted timescale is hours to years. The impacts of wind power on transmission depend on the location of wind power plants relative to the load, and the correlation between wind power production and load consumption. Wind power affects the power flow in the network. It may change the power flow direction, reduce or increase power losses and bottleneck situations. There are a variety of means to maximise the use of existing transmission lines like use of online information (temperature, loads), flexible AC Transmission Systems (FACTS) and wind power plant output control. However, grid reinforcement may be necessary to maintain transmission adequacy. When determining the reinforcement needs of the grid, both steady-state load flow and dynamic system stability analysis are needed [120, 121].

5.7.5. Adequacy of power generation

Impacted timescale is several years. This is about total supply available during peak load situations. System adequacy is associated with static conditions of the system. The estimation of the required generation capacity needs includes the system load demand and the maintenance needs of production units (reliability data). The criteria that are used for the adequacy evaluation include the loss of load expectation (LOLE), the loss of load probability (LOLP) and the loss of energy expectation (LOEE), for instance. The issue is the proper assessment of wind power's aggregate capacity credit in the relevant peak load situations taking into account the effect of geographical dispersion and interconnection. Local storage systems with high energy capacity are also starting to be used in some power systems and may have a strong impact of adequacy of power, when cost competitive [120, 121].

5.8. Establishment of grid code for wind generation

To increase wind penetration, wind turbines should provide proper supports to system operation, like the conventional generator. It is necessary to utilize the various control functions, such as active and reactive power control, of wind turbine which uses the advanced power-electronics technologies [122]. Major wind manufacturers of the world recently tend to produce the wind turbines which have these functions or provide wind farm systems in which these functions are included. However it may require additional cost and accordingly the voluntary investment of each individual wind power provider is hard to expect. Thus system operator should enact the grid codes for interconnection and operation of wind generation and demand technical requirements which need to maintain the stable operation of the system according to operating condition. The grid codes of advanced countries in wind generation and various regulations included can be a good example [123].

Some of the various codes and requirements introduced by the leading European countries are;

- a) Active power regulation
- b) Reactive power regulation
- c) Fault ride through capability
- d) Communications and notifications

5.8.1. Active power control

Active power regulation facilitates for the wind turbines or wind farms to receive dispatch orders from system operator and operate by them. This regulation can contribute to increase the installation of large-scale wind farm in small power systems, like Cyprus. European countries, such as Denmark, Norway, Germany, and Ireland, with high wind penetration in general have various regulations related to active power control [124, 125, 126 and 127]. In the case of Denmark, especially, system operators require detailed and strict rules on active power control to maintain the system stability against increase of wind generation. In addition to absolute power, delta, and ramp rate control, wind power turbines are regulated to have several active power control functions. As a result, Denmark

can be the developed country in which wind power penetration is over twenty percent of total domestic equipments despite the country having a small power system.

Regarding the active power controllability, wind farms or wind turbines should be capable to limit the active power production in the range from 20% to 100% of its rated capacity according to dispatch order. This regulation is not to be applied when the wind farm or wind turbine isn't able to produce active power as ordered due to low wind velocity. It means that wind turbine or wind farm should have the proper equipment and control system which enables each control, such as absolute power, delta, and ramp rate control, as defined in grid code.

As mentioned, one of these regulations is the absolute power limitations. It is the means that restrict maximum power output of wind generation systems according to requirements' of the occasions such that the expectation of wind power output exceeds the maximum penetration limit. Wind farm or wind turbine should have the function which decreases the output power to reference value. When the regulation is applied to actual operation, spinning reserve to compensate the variation of wind generation can be decreased and instabilities of active power balance due to sudden increase of wind generation can be prevented. The wind penetration limit of isolated power system is also to be calculated simultaneously considering the corresponding state of loads and generations at that time not minimum load condition. It means that installation of wind generation need not to be suppressed by wind penetration limit any more. Actual output power of wind generations is to be limited only by operating condition regardless of total installation capacity.

Another important regulation is the ramp rate limitations. For stable operation, this regulation limits the power gradient of wind generation to a set point defined by system operator when the output power of wind generations increases rapidly. The commitment of conventional generators decrease as the wind penetration largely increases. In this case, conventional generator committed may not decrease its output power according to rapid increase of wind generation simultaneously. It causes the frequency problem and unstable operation of power system in the worst-case. To prevent the frequency problem, this regulation limits the increasing speed of output power when the changes of load and wind generation are larger than total ramp rate capacity of conventional generators. Thus a set

point of this regulation should be assessed considering the load following capability of main thermal plants. In the case of system operator of Europe and Canada, only 10% of upward change per minute of wind generations is allowed in grid code [125,127]. In Denmark, system operator determines and instructs the power gradient limits base on system condition [124].

Similarly as ramp rate limitation, delta control which limits the wind power output below the available power by fixed amounts defined by system operator is necessary to secure the spinning reserve in small and isolated power system. It means that wind generations have to operate with its own reserve, like a conventional generator. Thus this regulation can be used to solve the problems caused by decrease of spinning reserve of conventional generation and increase of controlling power for wind generation. The delta control as well as ramp rate limitation in fact can be selective options excepting for an isolated power system with extremely high wind penetration. Figure 47 illustrates the practical application of active power regulations such as absolute power limitation, ramp rate limitation and delta control [128].

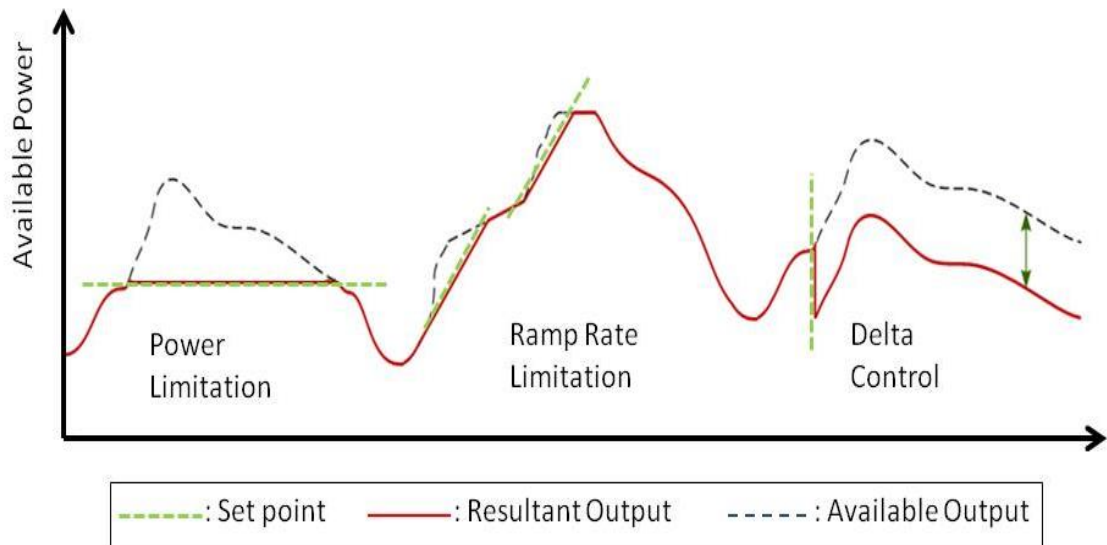


Figure 47: The practical application of active power regulations such as absolute power limitation, ramp rate limitation and delta control in order of left to right [128].

5.8.2. Reactive power control

To maintain the voltage of overall system stably, reactive power compensators should be equipped sufficiently and controlled continuously according to change of reactive power demand. The characteristics of reactive power consumption of entire power system can be changed largely according to erratic changes of wind generation and it may not be fully compensated due to decrease of conventional generation if the wind penetration is increased. Therefore wind turbines are required to have the reactive power compensation capability and the related equipments which come close to that of conventional generation recently. The related regulations can be founded from the grid code of many countries.

In the case of isolated power system of Cyprus that has low short circuit ratio (SCR), strict reactive power regulations should be applied to improve voltage stability. Thus it is important to use the DFIG type generators or direct drive type generator of the newest technology which are expected to have a controllability required in wind projects hereafter. It is also needed to improve the control system of existing wind generator to satisfy such various regulations in grid codes for wind generation [91].

The wind farms and wind generators should be capable to perform the reactive power control or voltage control at the point of common connection (PCC) according to system operators instructions if the power system is in normal operating condition. Because the existing wind generator of constant speed type needs the additional reactive power compensation to voltage control at the PCC, it was standard to operate the wind generators under the constant power factor regulation, especially unit power factor. However the wind generators of doubly fed induction generator (DFIG) type which is able to control reactive power continuously as well as active power using power electronic converters are used in the most wind farms recently.. Voltage control ensures the wind generators use its reactive capability efficiently and contribute the recovery of entire power system during and after fault. Therefore, the regulations for voltage control are included or planed to be included in grid code of advanced countries of wind generation, such as Denmark, Nordel, Canada, Ireland, and Germany [124, 129, 125, 126 and 127].

5.8.3. Fault ride through capability

It was common practice that the wind generators are disconnected immediately to prevent the damage of its equipment and system when the system voltage decreases under the certain level during a fault. Trip of wind generator and the accompanying loss of generation, however, can disturb the recovery of system and cause additional frequency problems as the wind penetration increases over a certain level [130]. To prevent these undesired trips of large wind generation due to under voltage and unstable operation, the regulation which requires the wind generator and wind farm to maintain the operation during the fault is being included in grid codes of many countries. This regulation is called 'Fault Ride through (FRT)' or 'Low Voltage Ride Through (LVRT)'. Most grid codes demand the wind generator to equip these FRT capabilities and make them support recovery of the system after the fault is cleared applying the additional requirements. Moreover, this regulation tends to strengthen to the Zero Voltage Ride through (ZVRT) in most countries [131]. Fault Ride Through regulations of various countries are presented in section 5.4.4 of this chapter. They have a lot in common defining the residual voltage, fault duration, and voltage recovery to maintain the operation of wind generation. Thus wind generators which are being connected to grid should maintain the operation and not be tripped even though low voltage is applied at the PCC during the fault if residual voltage and fault duration are upper side of the graphs. On the other hand, if the residual voltage becomes lower and fault duration longer than FRT capability, wind generators can be tripped to protect its equipment.

5.8.4. Communications and notifications

In order to achieve the above operations, example from Danish grid code, wind farms should be equipped with control system which ensures the remote and autonomous control of each wind turbine included in according to requirements described in grid code [124]. According to Danish grid code, for each wind farm the function called "farm controller" is to be implemented and ensure that regulating orders to the wind farm's total production are met in the connection point. The wind farm controller shall enable ordering of the various types of regulation as total orders which can be given both locally and via remote control and considering lots of wind turbines as just one wind farm.

Wind farms or wind generators should be equipped with a prediction system for active power estimation of the next day and notify active power prediction to system operator in advance. Then the predictions should be updated for certain time periods continuously to ensure the reliable market operation of power system. As the wind penetration increase, wind generation prediction is getting more important. If predictions for wind generation are not considered, power system should always prepare the reserve for entire wind capacity installed as well as the load change. This costs additional expenses and makes the system operate inefficiently. Thus in the system with high wind penetration, predictions for wind generations should be notified to system operator in advance so that system operator operates system and makes the plans efficiently. In Denmark, Ireland, and Canada, the regulations for active power prediction and notification are included in their grid codes and applied actually. Moreover, for accurate prediction of wind generation, the technical developments and various researches on the prediction of wind speed are being pursued actively. In the case of United Kingdom, especially, the regulations require that wind generator and wind farm perform the prediction for active power generation on a daily basis for the following 48 hours for each 30 minute time-period and notified to system operator.

CHAPTER 6

OPERATIONAL AND ECONOMIC REVIEW

This chapter provides an economic analysis of implementation of renewable energy technologies. Using the information from the projects all around the world, especially Europe, each technology is investigated. Each technology is then further optimized according to the conditions and resources of Cyprus. Following many simulations, results of the economic analysis is provided.

6. Operational and Economic Review

Without access to reliable information on the relative costs and benefits of renewable energy technologies it is difficult, if not impossible, for governments to arrive at an accurate assessment of which renewable energy technologies are the most appropriate for their particular circumstances.

The absence of accurate and reliable data on the cost and performance of renewable power generation technologies is therefore a significant barrier to the uptake of these technologies.

6.1. LCOE - Measure of cost of RES technologies

Cost can be measured in a number of different ways, and each way of accounting for the cost of power generation brings its own insights. The costs that can be examined include equipment costs (e.g. wind turbines, PV modules, solar reflectors), financing costs, total installed cost, fixed and variable operating and maintenance costs (O&M), fuel costs and the levelized cost of energy (LCOE). Equipment cost is the total cost of the equipment from the factory. Financial costs is sum of various financing costs such as debt closing costs, debt service reserve, construction financing, working capital reserve and other financing cost. Fixed and variable costs include salaries of the workers, rent for the land, cost of the utilities such as water, drainage and electricity as well as cost of equipment repairs, spare parts and cost of maintenance.

In order to create and run a valid analysis, whilst a renewable energy technology is being evaluated in comparison with a conventional technology, analyses of all analyzed technologies must be based on comparable characterizations [133]. Similarly, the analysis should be conducted on relevant and consistent macroeconomic and microeconomic base.

The analysis of costs can be very detailed, but for comparison purposes and transparency, the approach used in these studies is a simplified one. This allows greater scrutiny of the underlying data and assumptions, improving transparency and confidence in the analysis, as well as facilitating the comparison of costs by country or region for the same technologies in order to identify what are the key drivers in any differences.

The levelized cost of energy (LCOE) allows alternative technologies to be compared when different scales of operation, different investment and operating time periods, or both exist. Hence, in this study main solar and wind technologies will be compared against the conventional energy systems of Northern and South Cyprus based on their Levelized Cost of Energy (LCOE) of their sold or to be sold electrical energy.

The calculation for the LCOE is the net present value of total life cycle costs of the project divided by the quantity of energy produced over the system life.

$$LCOE = \frac{\text{Total Life Cycle Cost}}{\text{Total Energy Production}} \quad (4)$$

The initial investment in a PV system is the total cost of the project plus the cost of construction financing. The capital cost is driven by cost incurred such as land related costs which may include the mounting system, site preparation, field wiring and system protection, grid interconnection costs which may include electrical infrastructure such as inverters, switchgear, transformers, interconnection relays and transmission upgrades and project-related costs such as general overhead, sales and marketing, and site design which are generally fixed for similarly sized projects.

$$I = \text{Initial Investment} \quad (5)$$

In the LCOE calculation the present value of the annual system operating and maintenance (OM) costs is added to the total life cycle cost. These costs include inverter maintenance, site monitoring, insurance, land leases, financial reporting, general overhead and field repairs, among other items. OM costs are calculated using the formula 6 at below. Parameter N is the analysis period in years.

$$OM = \sum_{n=1}^N \frac{\text{Annual costs}^n}{(1-\text{Discount Rate})^n} \quad (6)$$

The present value of the end of life asset value is deducted from the total life cycle cost in the LCOE calculation. The net present value (NPV) can be calculated using the formula 7 at below.

$$NPV = \frac{Residual\ Value}{(1-Discount\ Rate)^n} \quad (7)$$

The value of the electricity produced over the total life cycle of the system is calculated by determining the annual production over the life of the production which is then discounted based on a derived discount rate. This can be calculated using the formula 8 at below.

$$TE = \sum_{n=1}^N \frac{Initial_{kWh}^{kWh} \times (1 - System\ Degradation\ Rate)^n}{(1 + Discount\ Rate)^n} \quad (8)$$

LCOE formula (4) is disaggregated using formulas 5, 6, 7 and 8 as follows:

$$LCOE = \frac{IOM - NPV}{TE} \quad (9)$$

6.2. Current Capital and O&M costs of RES technologies

6.2.1. Wind Projects

The installed cost of a wind power project is dominated by the upfront capital cost for the wind turbines (including towers and installation) and this can be as much as 84% of the total installed cost. The high upfront costs of wind power can be a barrier to their uptake, despite the fact there is no fuel price risk once the wind farm is built. The capital costs of a wind power project can therefore consists of combined costs of the turbines cost, civil works for site preparation and the foundations for the towers, grid connection and other ancillary costs such as site buildings, project consultancy etc [134].

The installed capital costs for wind power systems vary significantly depending on the maturity of the market and the local cost structure. China and Denmark have the lowest installed capital costs for new onshore projects of between USD 1300/kW and USD 1384/kW in 2010. Other low cost countries include Greece, India, and Portugal. Figure 48 tabulates the installed capital costs of various countries mainly from Europe [135,136,137] from year 2010.

Country	Price (\$/kW)	
	From	To
Australia	1991	3318
Austria	2256	2654
Canada	1975	2468
China	1287	1354
Denmark		1367
Finland		2100
Germany	1770	2330
Greece		1460
India		1460
Ireland		2419

Country	Price (\$/kW)	
	From	To
Italy		2339
Japan		3024
Mexico		2016
Netherlands		1781
Norway		1830
Portugal	1327	1858
Spain		1882
Sweden		2123
Switzerland		2533
UK		1734
United States		2154

Figure 48: Installed capital costs of onshore projects of various countries mainly from Europe [135,136,137]

The capital cost of offshore wind power is around twice that of onshore wind energy projects. The higher cost is due to increased investments in laying cables offshore, constructing expensive foundations at sea, transporting materials and turbines to the wind farm, and installing foundations, equipment and the turbines themselves. The turbines, although based on onshore designs, are also more expensive. They need to be designed with additional protection against corrosion and the harsh marine environment to help reduce maintenance costs, which are also higher offshore [139].

A recent Douglas-Westwood study initiated by The Research Council of Norway (RCN) provides a detailed analysis of offshore wind power [139]. The study describes recent trends in installed offshore wind power project costs, wind turbine transaction prices, project performance and O&M costs.

The largest cost component for offshore wind farms is still the wind turbine, but it accounts for less than half (44%) of the total capital costs. Based on a price assessment of wind turbines of the major manufacturers, and other research into the component costs, it was estimated that the average price of an offshore wind turbine was around USD 1970/kW. The foundations, electrical infrastructure, installation and project planning account 16%, 17%, 13% and 10% of the total costs, respectively [139]. Figure 49 summarizes the cost breakdown for a typical onshore wind power project [134].

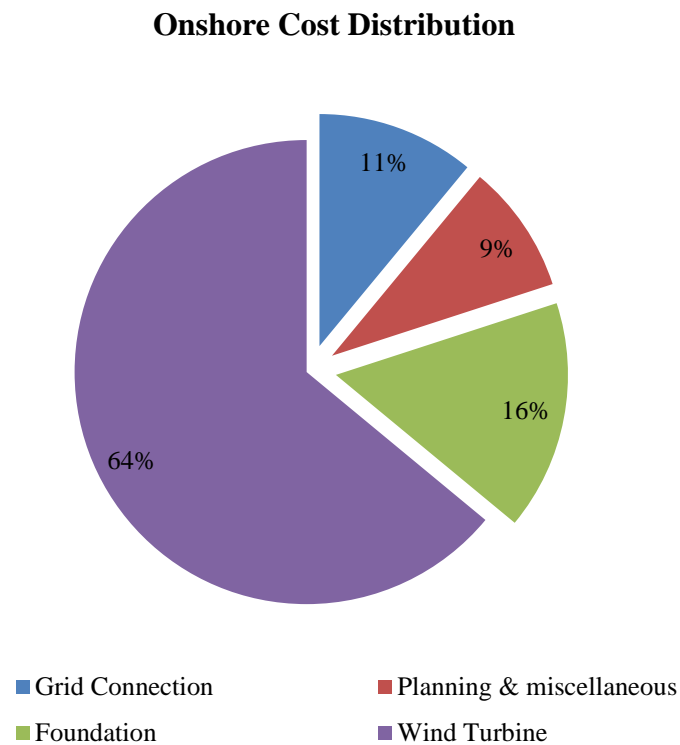


Figure 49: Cost breakdown for a typical onshore wind power project [134].

According to the estimates of [139], the current capital cost of the offshore wind power system for typical shallow water and semi-near shore conditions in the UK is USD 4471/kW which is almost 2.5 times higher than onshore wind case.

The overall capital cost for onshore wind farms depends heavily on wind turbine prices. They account for between 64% and 85% of the total capital costs and most, if not almost all, variations in total project costs over the last ten years can be explained by variations in the cost of wind turbines. Grid connection costs, foundations, electrical equipment, project finance costs, road construction, etc. make up most of the balance of capital costs.

Offshore wind costs can be high at around USD 4000/ kW or more, but installed capacity is still very low, and offshore wind offers the opportunity to have higher load factors than onshore wind farms, increasing the electricity yield. However, O&M costs will remain higher than onshore wind farms due to the harsh marine environment and the costs of access [135,136,137]. Figure 50 summarizes the cost breakdown for a typical offshore wind power project [134].

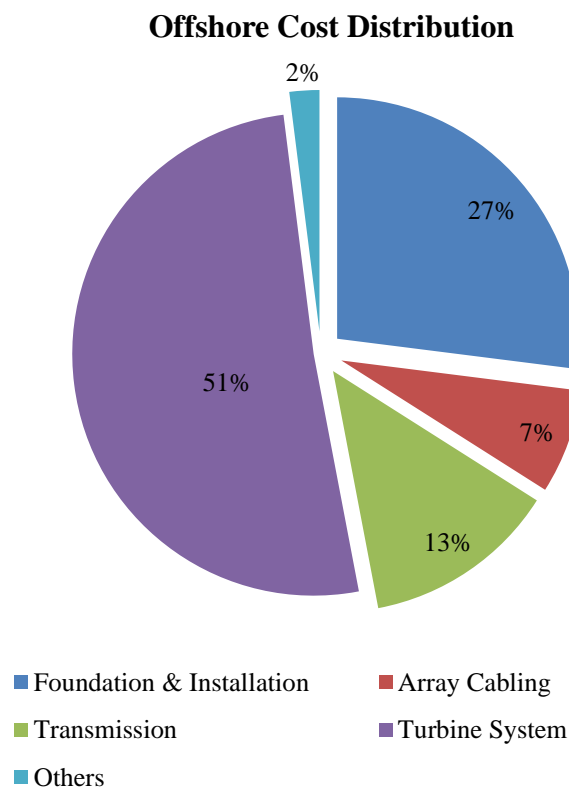


Figure 50: Cost breakdown for a typical onshore and offshore wind power project [134].

The overall contribution of O&M costs to the LCOE of wind energy is significant. Data for seven countries show that O&M costs accounted for between 11% and 30% of the total LCOE of onshore wind power. These countries include Denmark, Germany, Netherlands, Spain, Sweden, Switzerland and United States. The lowest contribution was in the United States and the highest in the Netherlands [137].

Best practice O&M costs are in the order of USD 0.01/ kWh in the United States. Europe appears to have a higher cost structure. The average O&M costs in Europe are at around USD 0.02/kWh and the best case at USD 0.015/kWh. [137].

Robust data for the O&M costs for offshore wind farms has yet to emerge. However, current wind farms have costs of USD 0.025 to USD 0.05/kWh in Europe [139].

6.2.2. PV Projects

The cost of electricity generated by a PV system is determined by its capital cost, discount rate, variable costs, amount of the solar irradiance and the overall efficiency of the system. Moreover, the capital cost is comprised of the PV modules and the balance of the system (BOS) cost. The BOS cost includes the costs of structural systems, site preparation costs and electrical system costs.

Accurate data on global average PV modules prices are difficult to obtain and in reality there is a wide range of prices, depending on the cost mechanisms of the manufacturer, the market structure and module efficiency.

According to report called Renewable energy technologies: Cost analysis series for solar photovoltaic by International Renewable Energy Agency (IRENA) published in June 2012, data from 92 utility scale PV projects averaging 10MW in 2010 in Canada, Australia, China, Thailand, India, Japan, the Czech Republic, Belgium, Greece, Spain, France, Germany, Italy and the United States resulted in an average installed price in 2010 of 4.71\$/W. Also, plants with capacity above 2MW do not appear to offer significant economies of scale. That is, the cost of a 20MW is not significantly lower than a 2MW plant [140]. Adding a tracking system increases the costs to an average of USD 6.39/W.

Lower financing costs can also be achieved, depending on the project specifics. One-axis tracking, although it increases capital costs by 10% to 20%, can be economically attractive because of the increase in energy-production (25% to 30% more kWh/kW/year in areas with a good solar resource) [141].

In 2010, the lowest price (USD 3.38/W) was recorded in Thailand, although this result was dominated by an 84 MW thin-film PV plant. The highest for utility-scale PV plants was recorded in Japan (USD 6.50/W), albeit the average project size is lower than in Europe and China. Among the major PV markets, Germany showed the lowest average price at USD 3.64/W for c-Si-based PV plants. It was noted that prices of c-Si systems (USD 3.65/W) were surprisingly close to those of thin-film systems (USD 3.61/W). The widest price variation occurred in Italy with lowest and highest figures of USD 2.89/W and USD 6.67/W. In the United States, the average price was USD 4.83/W, with an average capacity of 4.8MW [142]. Figure 51 illustrates the average prices and sizes of large utility scale PV plants by country in 2010.

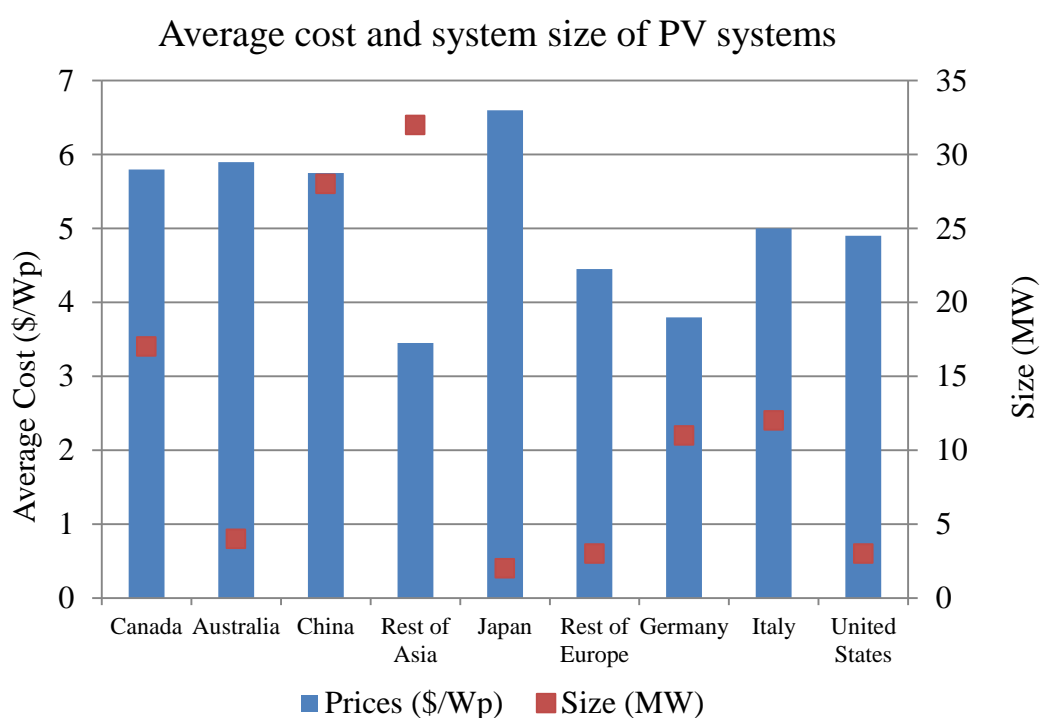


Figure 51: Average prices and sizes of large utility scale PV plants by country in 2010.

According to the Electric Power Research Institute's (EPRI) survey on PV O&M Best Practices, Utility-Scale PV Power Plant, which comprise of amorphous silicon based modules mounted at a fixed 30 degree tilt facing south, estimates total of 32 to 37 \$/kW-year and single axis tracking at 45 \$/kW-year [144]. This total includes scheduled and unscheduled maintenance, cleaning, inverter replacement reserve, insurance, property taxes and owner's costs.

6.2.3. Concentrating solar power (CSP) Projects

PV technologies, except concentrated PV, can use diffuse or scattered irradiance as well. However, CSP Technologies, unlike PV technologies, require large ($>5 \text{ kWh/m}^2/\text{day}$) direct normal irradiance (DNI) in order to function and be economic. Nevertheless, tracking the sun provides a significantly greater energy yield for a given DNI than a fixed surface and this is one of the main reasons that CSP using tracking systems.

Compared with conventional power plants, the levelized cost of electricity of CSP plants is formed by the initial investment cost. This investment cost can fulfil almost 80% of the total costs. The remaining 20% is for operation and maintenance costs as well as insurance costs.

CSP plants with thermal energy storage tend to be significantly more expensive, but allow higher capacity factors, the shifting of generation to when the sun does not shine and/or the ability to maximise generation at peak demand times. Costs increase, because of the investment in thermal energy storage, but also if the solar field size is increased to allow operation of the plant and storage of solar heat to increase the capacity factor. In technical terms, the field aperture area expressed as a multiple of the aperture area required to operate the power cycle at its design capacity is called the solar multiple value.

Although much depends on the design of the specific project and whether the storage is being used just to shift generation, or increase the capacity factor, the data currently available suggest that the incremental cost is economically justifiable, as CSP plants with storage have a similar or lower LCOE than those without. They also have lower O&M costs per kWh, because the fixed O&M costs, of which service staff is the largest contributor, are lower per megawatt as the plant size increases.

NREL has developed a model for conducting performance and economic analysis of CSP plants. The model can compare various technology options and configurations in order to optimise the plant design. Figure 52 shows the relationship between capacity factor (20% to 60%) and thermal energy storage in hours (h) for different solar multiples in regions with a good solar resource. The trade-off between the incremental costs of the increased solar field and the storage system must be balanced against the anticipated increase in revenue that will accrue from higher production and the ability to dispatch power generation at times when the sun is not shining [144].

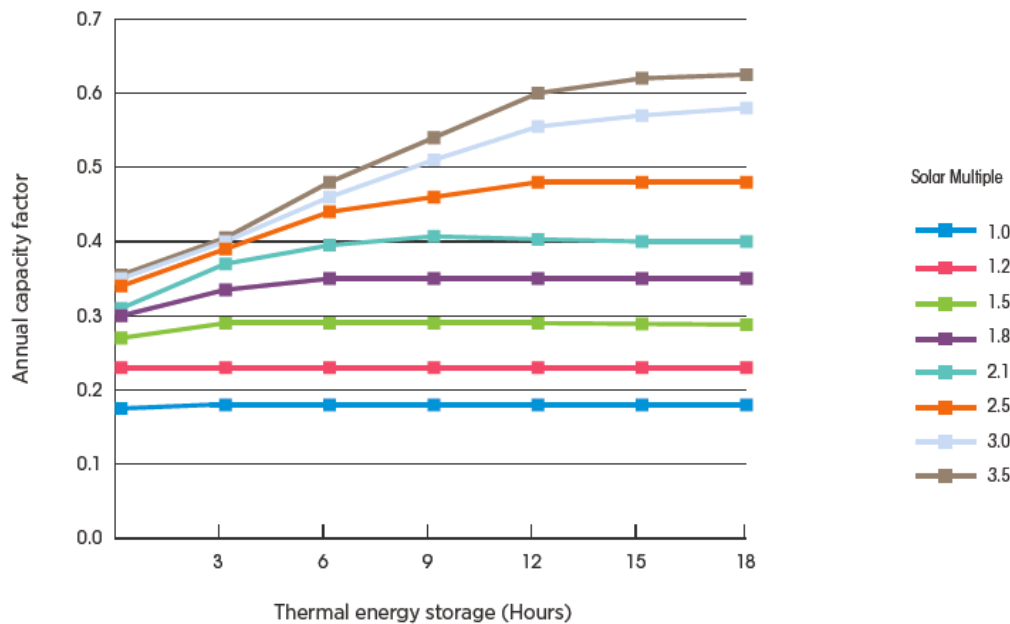


Figure 52: Annual capacity factor for a 100MW parabolic trough plant as a function of solar field size and size of energy storage [144].

The current investment cost for parabolic trough and solar tower plants without storage are between \$ 4500-7150/kW. Figures 53 and 54 tabulate the various capital costs and key characteristics of parabolic trough and solar tower plant from various surveys. The cost of parabolic trough and solar tower plants with thermal energy storage is generally between \$5000-10500/kW [144,145,146,147,148,149].

	Heat transfer fluid	Solar Multiple	Storage (hours)	Capacity factor (%)	Cost (\$/kWe)
Parabolic	Synthetic oil	1.3	0	26	4600
	Synthetic oil	1.3	0	23	7144
	Synthetic oil	2	6	41	8000
	Synthetic oil	2	6.3	47	8950-9810
	Synthetic oil	2	6	43	7732
	Molten Salt	2.8	4.5	50	7380
		2.5	9	56	7550
		3	13.4	67	9140

Figure 53: Capital costs and key characteristics of parabolic trough and solar tower plant - Part 1 [144,145,146,147,148,149].

	Heat transfer fluid	Solar Multiple	Storage (hours)	Capacity factor (%)	Cost (\$/kWe)
Solar Tower	Molten Salt		7.5		7280
	Molten Salt	1.8	6	43	6300
	Molten Salt	2.1	9	48	7427
	Molten Salt	1.8	6	41	7463
	Molten Salt	2	9	54	7720
		3	12	68	9060
		3	15	79	10520

Figure 54: Capital costs and key characteristics of parabolic trough and solar tower plant - Part 2 [144,145,146,147,148,149].

Looking at a wider range of parabolic trough projects, based on data from four sources, highlights that the solar field is by far the largest cost component and accounts for between 35% and 49% of the total installed costs of the projects evaluated [147, 146, 144, 145]. However, care must be taken in interpreting these results, as the cost breakdown depends on whether the project has thermal energy storage or not. The share of the thermal energy storage system varies from as low as 9% for a plant with 4.5 hours storage, to 20% for a plant with 13.4 hours storage. The heat transfer fluid is an important cost component and accounts for between 8% and 11% of the total costs in the projects examined. A detailed breakdown of parabolic trough project costs is given in figure 54.

For example, a turn-key 50 MW parabolic trough power plant similar to the Andasol plant in Spain, assuming has storage capacity of 7.5 hours, is estimated to cost USD 364 million or USD 7280/kW [148].

The solar field equipment (510 000 m²) is the most capital-intensive part (38.5 %) of this parabolic trough system. The price of a solar collector is mainly determined by the cost of the metal support structure (10.7 % of the total plant cost), the receiver (7.1 %), the mirrors (6.4 %), the heat transfer system (5.4 %) and the heat transfer fluid (2.1 %). The thermal energy storage system accounts for 10% of total costs, with the salt and the storage tanks being the largest contributors to this cost.

Labour represents 17% of the project cost and is an area where local content can help reduce costs in developing countries. Based on experience with Andasol 1, the site improvements, installation of the plant components and completion of the plant will require a workforce of around 500 people.

The cost breakdown for typical solar tower projects is different from that of parabolic trough systems. The most notable difference is in the cost of thermal energy storage. The higher operating temperature and temperature differential possible in the storage system significantly reduces the cost of thermal energy storage. In the analysis of a system with nine hours of storage, the thermal storage system of the solar tower project accounts for 8% of the total costs, while for the parabolic trough it is 16%.

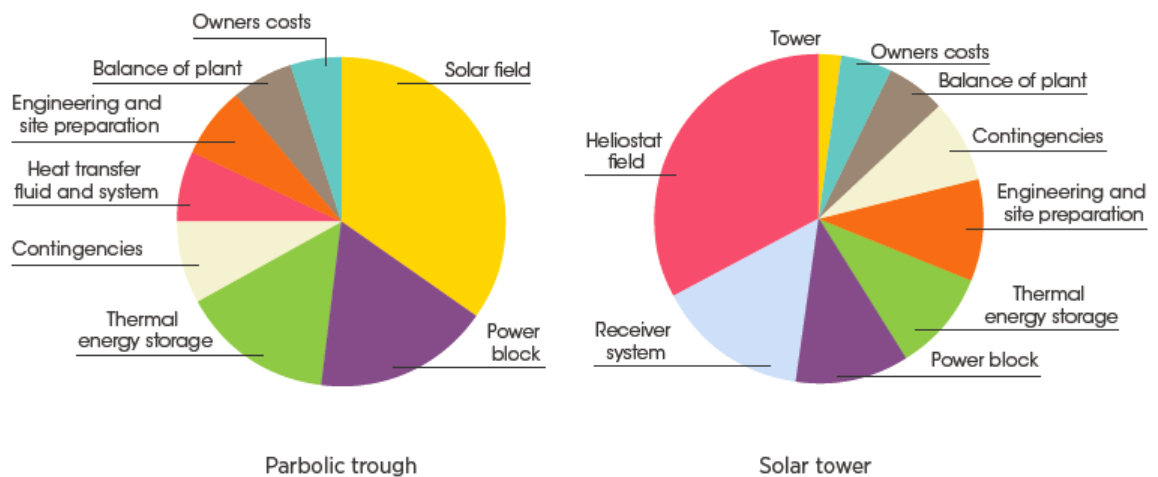


Figure 55: Total installed cost breakdown for 100MW parabolic trough with 13.4 hours of thermal storage and solar tower with 15 hours of thermal storage [147].

The operating costs of CSP plants are low compared to fossil fuel-fired power plants, but are still significant. The O&M costs of recent CSP plants are not publically available.

It is currently estimated that a parabolic trough system in the United States would have O&M costs of around USD 0.015/kWh, comprised of USD 70/kW/year fixed and around USD 0.003/kWh in variable costs [144]. However, this excludes insurance and potentially other costs also reported in other O&M cost estimates. For solar towers, the fixed O&M costs are estimated to be USD 65/kW/year [146].

6.3. Future Capital and O&M cost of RES Technologies

6.3.1. Wind Projects

Wind turbine cost reduction in the last two decades, for both onshore and offshore wind turbines, have been achieved by economies of scale and learning effects as installed capacity has grown.

The LCOE of wind has been further reduced as the result of higher capacity factors that have come from increasing turbine height and rotor diameter. The growth in the average size of onshore turbines will slow as increasing wind farms heights on land will become increasingly difficult. The increase in the average size of offshore wind turbines will continue as increased rotor height and diameter allow greater energy yields. However, the increase in the size of turbines and blades also increases their weight, increasing the cost of towers and the foundations. Historically the increase in the weight of turbines has been limited by the utilisation of lighter materials and the optimisation of design, although it is not clear if this trend can continue. As a result, there appears to be relatively small economies of scale from larger turbines, their main benefit being increased energy yield and scale given to wind farms [163].

The cost of grid connection is not likely to decline significantly for onshore wind farms. However, offshore developments can expect to see cost reductions as the scale of wind farms developed increases and the industry capacity increases. The cost of long distance grid connections for wind farms far from shore could be reduced by using HVDC (high voltage direct current) connections. Costs are coming down for these connections and lower losses could make them more economical overall, even taking into account the cost of converting the DC to AC onshore. The costs for the internal grid connection are estimated to be constant and only contribute a minor share of investment costs associated with an offshore wind farm [163].

The foundations can account for 16% of onshore wind farm costs and 27% for offshore wind farms [134]. The largest cost components of foundations are cement and steel. Actual foundation costs will therefore be strongly influenced by these commodity prices. However, some cost reductions are still possible as costs will increase somewhat less proportionally than the increase in swept rotor area, so larger turbines will help reduce specific installation costs in some degree [164]. Other cost reductions can come from economies of scale, reduced material consumption through more efficient designs and

reduced material cost. It has been estimated that if steel costs decline by 1-2% per year then this can result in a 5-10% reduction in overall foundation costs [165].

The potential for reducing the cost of offshore wind turbine is higher than for onshore. Offshore foundations are typically at least 2.5 times more expensive than onshore ones [139]. The trend to larger wind turbines, improved designs, reduced installation times and larger production lines for foundations will help reduce costs [163].

However, for shallow and fixed foundations, cost reduction will be modest. For deeper offshore foundations the dynamics are more complicated. Fixed seabed foundations in greater than 20 meters of water become increasingly expensive as deeper piles are required and wave and current forces can be greater. Significant cost reductions are therefore not obvious. It is likely that fixed seabed foundations will be uneconomic beyond a depth of around 40 meters and floating foundations will be required.

Floating foundations are more expensive than shallow monopole foundations, but cost reduction potentials are significantly larger, as a range of innovative designs are being explored. Today's floating foundations are predominantly demonstrator projects. As experience is gained and R&D advances, designers will be able to identify foundation types with the greatest potential. The cost of floating foundations could decline by 50% by 2030, although they are still likely to be a third more expensive than shallow monopole foundations [138].

Installation and commissioning costs, particularly for offshore wind farms, could be reduced, despite the increasing size and weight of turbines making this process more difficult. Specialized installation vessels will provide reduced installation times.

However, the largest cost reduction possibility is the so-called "all in one" installation, where the wind turbine is fully assembled onshore, transported to the already installed foundation and installed in one piece. This technique is just beginning to be evaluated, with two projects to date having used this method: the Beatrice Demonstrator in Scotland and the Shanghai Bridge project in China. Turbine installation costs offshore could be reduced by as much as 30% by 2030 [138].

Speeding up the installation process and electrical installations should help reduce commissioning time significantly, reducing working capital requirements and bringing forward the date when the first revenue from electricity sales occurs.

The capacity factor for a wind farm is determined by the average wind speed at the location and the hub height. The energy that can be harvested is also a function of the swept rotor area. Thus, tall turbines with larger rotor areas in high average mean wind speed areas will have the highest capacity factors and energy yields. One of the main advantages of offshore wind power is its ability to obtain increased capacity factors compared to equivalent capacity onshore installations. This is due in part to opportunities to place the wind farms in high average wind speed environments, but also because objections to very tall wind turbines are sometimes less of an issue [163].

Considerable information on wind resource mapping across Europe and the USA has been accumulated and it is extending to other areas of the world, where the development of wind power has the potential to contribute to the energy mix. Increased access to wind mapping information will have a significant impact on maximizing yield and minimizing generation cost by reducing the information barrier to identifying the best sites for wind farm development [163].

Continuing improvements in the ability to model turbulence with computational fluid dynamics can help improve designs and increase the responsiveness of machines in turbulent conditions. At the same time, the use of radar on top of the nacelle to “read” the wind 200 to 400 meters in front of the turbine can allow appropriate yaw and pitch adjustments in anticipation of shifts or changes in the wind. It is thought that these improvements will both increase efficiency and reduce wear and tear on the machine by reducing the frequency and amplitude of shear loads on the rotor [163].

The IEA and GWEC assume that the learning rate will be slightly lower than the historical average at 7%, hence cost reductions to 2015 are in the range of 5% to 11%, while by 2020 the estimated cost reduction range widens to 9% to 22% [135, 167].

Estimates of the cost reduction potential for offshore wind are quite uncertain given the fact that the offshore wind industry is just at the beginning of its development. Recent analysis has identified cost reduction potentials of 11% to 30% by 2030, depending on how

rapidly the industry expands [138]. The key to reducing costs will be through learning effects, more R&D, wind turbine capacity increases, expansion of the supply chain, greater dedicated installation capacity (to reduce reliance on offshore oil and gas industry) and more competition.

However, cost reduction potentials could be higher, as supply chain constraints and lack of competition have been estimated to have inflated installed costs by around 15% [168]. In this scenario, learning effects, moving to larger wind farms with larger turbines, increased supply chain development, and greater competition – as well as potential breakthroughs from novel wind turbine designs and foundations – could see costs fall by 28% by 2020 and by 43% by 2040. However, these reductions remain highly uncertain and variations of plus or minus 20% in 2040 are possible. Taking into account the increased capacity factors achieved by offshore wind turbines as they get continually larger means that capital costs (undiscounted) per MWh generated could drop by 55% by 2040 [168].

6.3.2. PV Projects

The PV module itself accounts for around half of total PV system costs. The continued reduction in PV modules costs is therefore a key component of improving the competitiveness of PV.

While c-Si PV is the most mature PV technology, there still exists significant room for reducing manufacturing costs through technology innovation and economies of scale. According to one study both low- and high-cost manufacturers could halve their production costs by 2015. The costs of poly-silicon and wafer production could decline dramatically by 2015 driven by the increasing scale of production and ongoing manufacturing innovations. The estimated total PV module cost of USD 1.75/W will reduce to USD 0.75/W [169].

Alternative studies project a similar decline in PV module prices by 2015. Solarbuzz projects that c-Si PV module prices will decline from USD 2.17/W in 2010 to as low as USD 1.07/W in 2015 [170]; Lux Research projects a slightly less aggressive decline to around USD 1.2/W in 2015 [171]. Given the rapid cost reductions in 2011, these projections for average c-Si module prices are likely to be bettered.

The BOS and installation costs will become proportionately more important over time as PV module costs continue to decline. Therefore, BOS cost reductions will become vital to continuing the rapid LCOE cost reductions of PV systems. Among BOS components, the cost of the inverter is generally well-known while this is often not the case for remaining electrical, structural and installation costs, which vary widely depending on local conditions and labour costs.

Achieving cost reductions is more challenging for BOS equipment than for PV modules because BOS involves a number of different components and suppliers, more mature technologies, and is, and will probably always be due to its nature, a less integrated industry. However, technological developments to optimize physical design and reduce BOS costs are still possible. There are many possible design strategies, but further work will be required to identify what combination of approaches is optimal in different circumstances and markets [172, 173]. The most important factors to reduce BOS and installation costs are outlined below. These factors together could result in BOS and installation cost reductions similar to those for PV modules.

Electrical system improvements start with efforts to improve the design of the inverter. Historically, inverter costs have trended down with PV module costs. Continued investment in R&D and improvements in manufacturing processes should allow this trend to continue. One interesting area of development and cost reduction is the use of micro-inverters directly integrated into the PV modules, which also reduce the installation cost. Also important for both inverters and micro-inverters are efforts to increase the lifetime from today's 5-10 years which is significantly shorter than the lifetime of the PV system life. All of these efforts are projected to halve inverter costs by 2020 [168].

Structural system improvements include downsizing of the structural components. This could yield up to 40% of the BOS cost reductions. Efficient designs to minimize the structural stress caused by wind could result in significant reduction in the structural costs by allowing lighter, cheaper structures [172].

Installation costs can be reduced with continued experience, increased market scale and competition. Process automation and high-level pre-assembly and standardization could reduce labour costs for installation by up to 30% [172].

Standardization and economies of scale will help reduce component costs by high volume manufacturing of BOS components. The potential cost reduction is large, as most BOS component manufacturers today are small companies. Large companies are pursuing important economies of scale strategies to remain competitive [172].

Important improvements could be obtained for PV modules, BOS and electronics if the PV efficiency improves and the area required for a given generation capacity decreases. As a rule of thumb, every 1% increase in PV module efficiency reduces the BOS cost by between USD 0.07 and USD 0.10/W [174].

While for physical reasons PV modules will never reach the maximum theoretical cell efficiency or the highest cell efficiency obtained at laboratory level, the efficiency of the current commercial modules still has significant room for improvement. Analysis suggests that efficiency improvements may occur for all PV commercial modules [171]. By 2015, the efficiency of the best commercial mono-crystalline Silicon modules could be well above the current 20%, while the average efficiency of multi-crystalline c-Si modules could approach 17% and commercial CIGS thin-film modules (with a current efficiency of 10%-13%) could rival today's c-Si module efficiency.

Taking into account the near-term market growth, large-scale PV plants are projected to reduce system costs from between USD 3730 to USD 3900/kW in 2011 to USD 2200 to USD 2640/kW by 2015 [170]. Utility scale systems can expect to achieve similar reductions by reducing to USD 1800/kW in 2020 and as low as USD 1060 to USD 1380/kW by 2030. These projections might be too conservative in the medium- to long-term given that they are based on a learning rate of 18%, which is less than the historical rate of 22%. However, this uncertainty is balanced by the possibility that the learning rate will reduce slowly over time as the technology becomes more mature.

6.3.3. CSP Projects

The LCOE from CSP plants can be reduced by improving performance (efficiency) and reducing capital costs.

There are specific capital cost reduction opportunities, while improvements in the performance of the CSP plant will reduce the “fuel cost”, for instance by reducing the size of the solar field for a given capacity.

Although CSP plants have a similar basic component breakdown (e.g. solar field, HTF, power block), the reality is that many of these components are materially different for each CSP technology. However, some of the cost reduction potentials are more generic, for instance from scaling up plant size and increased competition among technology suppliers. This section discusses the generic and technology-specific cost reduction opportunities.

CSP is only just beginning to be deployed at large scale and, for a variety of reasons; many of the installed plant are relatively small. Increasing the scale of plants will be an important cost reduction driver. For example, current parabolic trough CSP projects under development in the United States have capacities of 140 MW to 250 MW while solar tower projects are in the 100 to 150 MW scale for individual towers [148].

One artificial constraint in Spain has been the fact that the Spanish feed-in tariff law (RD-661/2007) stipulates a maximum electrical output of 50 MW for eligibility. However, in terms of economies of scale, 50 MW is not the optimal plant size. The specific costs of a parabolic trough power plant with 7.5 h of storage can be cut by 12.1% if the plant size is increased from 50 MW to 100 MW and by 20.3% if it is increased from 50 MW to 200 MW. Following various analysis, it is identified that increasing plant size from 50 MW to 120 MW could reduce capital costs by 13% [177].

The largest cost reductions come from the balance of plant, grid access, power block and project management costs. The project development and management are almost constant for each project size, so the specific costs decline significantly as the plant capacity increases. In contrast, the costs of the solar field and storage are directly related to the plant size, so only small economies can be expected.

Key components to reduce the solar field cost are support structures, including foundations, mirrors and receivers. These costs will tend to decline over time as the overall volume increases. For the support structures, developers are looking at reducing the amount of material and labour necessary to provide accurate optical performance and to meet the designed “survival wind speed”. Given that the support structure and foundation can cost twice as much as the mirrors themselves, improvements here are very important.

For mirrors, cost reductions may be accomplished by moving from heavy silver-backed glass mirror reflectors to lightweight front-surface advanced reflectors (e.g. flexible aluminium sheets with a silver covering and silvered polymer thin film). The advantages of thin-film reflectors are that they are potentially less expensive, will be lighter in weight and have a higher reflectance. They can also be used as part of the support structure.

However, their long-term performance needs to be proven. Ensuring that the surface is resistant to repeated washing will require attention. In addition to these new reflectors, there is also additional work underway to produce thinner, lighter glass mirrors.

Lighter mirrors will reduce support structure and foundation costs, while some thin-film mirror designs can even contribute part of the structural load themselves. For parabolic troughs, wider troughs with apertures close to 7 m are being developed and could offer cost reductions over current systems with a 5-6 m aperture. Advanced reflector coatings are under development to increase reflectivity from current values of about 93.5% to 95% or higher. Coatings are also being explored to reduce the frequency of cleaning required and water consumption. Given that there is a one-to-one correlation between optical efficiency of the mirrors and receivers, and the LCOE of CSP plants, even these small improvements are important. For the receivers, reducing the emittance of long wave radiation, while maintaining the high absorption of short wave radiation (sunlight) is being pursued to improve performance. This is important; because today’s evacuated tube receivers can be designed to have virtually zero conduction and convection heat losses to the environment, meaning that radiation is the only important heat loss. Thus, the pursuit of selective coatings with very low, long-wave emittance is an important R&D goal, while these receivers will also need to be designed for cost-effective operation at higher temperatures. Improved diagnostic systems to help identify degraded receiver tubes will help maintain performance over time [149].

The use of an inert gas instead of a vacuum could result in lower cost receivers and would also help reduce or even eliminate hydrogen infiltration. The problem with current heat transfer fluids is that hydrogen can permeate into the evacuated tube and result in greatly increased heat rate losses. Given that a CSP plant with hydrogen infiltration in 50% of its receivers will produce electricity at USD 0.03/kWh more than one without, this is a serious cost issue [149].

For solar towers, the largest cost components of the solar field are the mirror modules, the drives and finally the foundation, pedestal and support structure. It is still not clear what size heliostats are optimal, or indeed if there is an optimal size [149]. Larger heliostats reduce the cost of wiring, drives, manufacturing and controls but have higher foundation, pedestal and support structure costs. Overall, larger heliostats appear to have a cost advantage, particularly if mass produced. Long-run costs could be as low as USD 137/m² for 148 m² heliostats that are produced at a rate of 50 000 per year. This compares to the estimate for today's cost at USD 196/m², and USD 237/m² for today's smaller 30 m² heliostat. The trade-off is that smaller heliostats will have an improved optimal performance, which could reduce the cost gap by as much as USD 10/m² [149].

For the mirrors, improving the optical efficiency is critical. Developing highly reflective surfaces with the required durability is the first step. At the same time, the development of better passive methods to reduce soiling and active cleaning measures with low water costs will help reduce O&M costs. Water costs are important since most of these systems are located in arid regions.

Solar field components, such as drives and controls, are expensive and cost reductions can be achieved. Future azimuth drives for solar tower heliostats should be lower in cost and have optimised controls to ensure the better focussing of the incoming solar radiation on the receiver. Reducing the specific costs of the foundations, pedestal and support structures can be achieved by having smaller heliostats, as the requirements to resist maximum wind speeds are lower, while stability is also improved, helping focusing. However, the remaining costs are higher, particularly for controls and wiring, but also for drives and installation. Better design tools will help optimise support structures and reduce material costs, but, as already noted, it is not yet clear if there will be an optimal size.

The solar tower receiver costs are dominated by the tower, around one-fifth of the cost, and the receiver around 60% of the cost [148]. Cost reductions are possible, but the focus will be on improving the performance of the receiver to reduce the LCOE of solar tower plants. An important opportunity is the increase in generating efficiency that can be achieved by moving to an ultra-supercritical Rankine cycle. This would require receivers that could provide outlet temperatures of 650°C and support higher internal temperatures. Improving solar absorptivity, reducing infrared emissivity and reducing thermal losses through optimised materials and designs will help reduce costs and improve performance. The use of direct steam receivers, rather than a heat transfer fluid in the receiver, could yield LCOE reductions, but designs are currently based on conventional boilers and need to be adapted to CSP plants.

The overall cost reductions for parabolic trough solar fields, taking into account efforts in all areas, could be in the range 16% to 34% by 2020 [178]. It is important to note that, all other things being equal, a given percentage improvement in the performance of the solar field will yield a 50% larger reduction in the base LCOE than that.

Higher operating temperatures will allow an increase in the electrical efficiency of CSP plants, reduce the cost of the thermal storage system (as a smaller storage volume is needed for a given amount of energy storage) and achieve higher thermal-to-electric efficiencies. Most current commercial plants use synthetic oil as the heat transfer fluid. This is expensive and the maximum operating temperature is around 390°C. The use of molten salt as the HTF can raise the operating temperature up to 550°C and improve thermal storage performance. In the solar towers, the higher concentration ratio could enable even higher operating temperatures. A temperature level of 600-700°C is compatible with commercial ultra-supercritical steam cycles that would allow the Rankine cycle efficiency to increase to 48%, compared with perhaps 42% to 43% for today's designs [149].

Super-critical carbon dioxide is also being explored as a HTF to enable higher operating temperatures. Higher temperatures than this would require the use of gas-based cooling and thermodynamic cycles. A number of design options (coolants, such as water, steam, salts, air, gases and various thermodynamic cycles) are being considered to exploit this potential.

The overall cost reductions for the HTF in parabolic trough CSP plants by moving from synthetic oil to molten salt could be on the order of 40% to 45% by 2020 and allow operating temperatures in the solar field to increase from 390°C to 500°C, with associated benefits from increased steam cycle efficiency [178].

An important issue is the cooling need of the CSP thermodynamic cycle, which may either increase the investment cost or constrain the CSP deployment where water availability is limited. Current wet-cooled CSP plants require around 2 100 to 3 000 litres/MWh [135, 146] which is more than gas-fired power plants (800 litres/MWh), but the lower end of the range is similar to conventional coal-fired plants (2000 litres/MWh).

Strategies to reduce the freshwater consumption include: the use of dry cooling technology; the use of degraded water sources; the capture of water that would otherwise be lost; and increasing thermal conversion efficiencies. Dry cooling has by far the greatest potential to reduce water consumption. Dry cooling also has the advantage of reducing parasitic loads. Hybrid cooling is also an option where very high ambient temperatures would not allow adequate cooling. In hybrid systems the CSP plant is predominantly dry cooled; wet cooling is used when ambient temperatures rise to the point where dry cooling becomes inadequate.

Today's state-of-the-art thermal energy storage solution for CSP plants is a two-tank molten salt thermal energy storage system. The salt itself is the most expensive component and typically accounts for around half of the storage system cost [149], while the two tanks account for around a quarter of the cost. Improving the performance of the thermal energy system, its durability and increasing the storage temperature hot/cold differential will bring down costs.

For solar towers, increasing the hot temperature of the molten salt storage system should be possible (up to 650°C from around 560°C), but will require improvements in design and materials used. The development of heat transfer fluids that could support even higher temperatures would reduce storage costs even further and allow even higher efficiency, but it remains to be seen if this can be achieved at reasonable cost. If direct steam towers are developed, current storage solutions will need to be adapted, if the capacity factor is to be increased and some schedulable generation made available.

The cost reduction potential for thermal energy storage systems, when combined with increases in the operating temperature and hence temperature differential in the storage system, is significant. Thermal energy storage costs could be reduced by 38% to 69% by 2020 [178].

Cost reductions in the power block will be driven largely by factors outside the CSP industry. However, cost reductions for the balance of plant should be possible, particularly for the molten salt steam generators in solar tower plants. Another important area for LCOE reductions is in reducing parasitic losses which can be quite high, with 10% thought to be achievable for future solar tower projects [149] while for parabolic troughs, it is currently in the range of 13% to 15% [178].

There are relatively few CSP technology suppliers today given that the CSP industry is in its infancy and current suppliers have higher margins than the more mature and competitive PV industry [148]. As the industry grows, the number of technology suppliers should increase and costs should come down with increased competition. Greater competition is also likely to help boost technology development and innovation.

Recent analysis of cost reduction and deployment potential for CSP technologies has identified significant overall cost reduction potentials [135, 146, 178, 149].

For troughs, significant reductions are expected for thermal energy storage and the HTF system. This is expected to result from operating troughs at higher temperatures. This will allow a larger difference between the hot and cold fluid temperatures for both the HTF and storage medium, which will reduce HTF pumping requirements and also the volume and cost of the thermal storage system. Taking into account reductions in other areas, an overall reduction of 41% in the capital cost is projected.

For towers, the greatest reductions are expected in the cost of the solar field, which is predicted to fall by 40%. The overall reduction in capital cost projected for the generic plant solar tower plant is around 28%.

Overall capital cost reductions for parabolic trough plants by 2020 are estimated to be between 17% and 40% [145, 178]. For solar towers the cost reduction potential could be as high as 28% on a like-for-like plant basis [145].

Alternative analysis suggests that the evolution of costs and performance is more complex, with the possibility that capital costs might decline by between 10% and 20%, depending on the components by 2017, but, from an LCOE perspective, a better solution would be to have overall installed costs that are around the same as today, but use the cost reductions to increase the thermal energy storage and solar field size to increase the capacity factor from 48% to 65% [149].

Looking out slightly further to 2020 and assuming higher cost reductions (from one-fifth to one-third, depending on the components) and the switch to super-critical Rankine cycles, capital costs could be reduced by 24% and the capacity factor rose to 72% [149].

In addition to industry expectations and bottom-up engineering-based estimates of cost reductions, cost reduction potentials can be derived by looking at the historical “experience curve” or “learning rate” for CSP.

Learning curves estimate the percentage cost reduction for each doubling of the installed capacity. However, given the early stage of deployment of CSP technologies and the stop-start nature of the industry so far, the learning rate for CSP is highly uncertain. Estimates in the literature vary, but 8% to 10% have been suggested as a realistic range, if perhaps slightly conservative [135, 176]. This is an average figure; the learning rates for the solar field, HTF, thermal energy storage and the balance of plant will be higher than this, given they are the most innovative part of a CSP plant. The power block is based on mature technology and a lower learning rate than the average is expected [175].

Cost reductions by 2020, assuming a learning rate of between 8% and 10%, will depend on the rate of growth in CSP deployment. However, given the large number of CSP projects either under construction or soon to be constructed, cost reductions of as much as 30% to 40% maybe possible in an aggressive deployment scenario to 2020 [135]. Given the uncertainty over cost reductions in the near term, overall cost reductions of 10% are assumed by 2015. This includes the impact of improved performance and higher thermal energy storage-increasing capacity factors. The cost reduction on a strictly like-for-like plant basis would be somewhat higher than this.

The opportunities to reduce O&M costs are good. There is currently little long-term experience in operating CSP plants. It is only now that the lessons learned in California since the 1980s are beginning to be applied in today's designs. The key areas to address are: broken mirrors, receiver failure, more automation of maintenance activities/better preventive maintenance, plant designs that reduce O&M costs.

A significant problem with earlier plants was broken/cracked mirrors or mirrors separating from their pads, with most of this damage coming from the effects of wind loads. This led to loss of reflectance, accounting for a fifth of all lost power production outages [144], so the costs are higher than just the O&M costs to fix or repair the mirrors. Reducing the rate of breakage and loss of reflectance can therefore help reduce costs significantly.

This can be achieved with thin-film reflectors, laminated mirrors and reinforcing vulnerable reflectors (for instance at the edge of the solar field, where there is no mutual shelter from winds) [144].

Receiver failure in parabolic trough plants (i.e. breakage, hydrogen infiltration, vacuum loss and coating degradation) is another area that can be targeted for cost reduction. The SEGS plants were able to reduce breakage to 3.4%, but this still results in high costs in terms of replacement and lost output [144]. More robust receivers would help to reduce failures, but there currently is not enough data for new plants to identify the key causes of failure and allow improved designs. This is an area where ongoing research and monitoring of recent plants is warranted in order to identify the key failure mechanisms and how best to address them. More automation of maintenance activities and better real-time diagnostics could help reduce O&M costs, as well as improve performance. For example, automated washing of only those mirrors with known degraded performance could help reduce costs. Improved plant designs that also aim to minimise O&M costs will evolve as operating experience with the new generation of CSP plants emerges.

Overall cost reduction potentials for O&M costs could be in the range of 35% by 2020 for parabolic trough plant and 23% for solar towers [144]. Given these figures, it is assumed that O&M costs could be reduced by between 5% and 10% by 2015.

6.4. Introduction to the System Advisor Model (SAM)

The software tool called System Advisor Model (SAM) has been used in this study [132]. SAM is a performance and financial model designed to facilitate decision making for people involved in the renewable energy industry. SAM was developed by the National Renewable Energy Laboratory in collaboration with Sandia National Laboratories in 2005, and at first used internally by the U.S. Department of Energy's Solar Energy Technologies Program.

Since the first public release in 2007, over 35,000 people representing manufacturers, project developers, academic researchers, and policy makers have downloaded the software. Manufacturers are using the model to evaluate the impact of efficiency improvements or cost reductions in their products on the cost of energy from installed systems. Project developers use SAM to evaluate different system configurations to maximize earnings from electricity sales. Policy makers and designers use the model to experiment with different incentive structures [132].

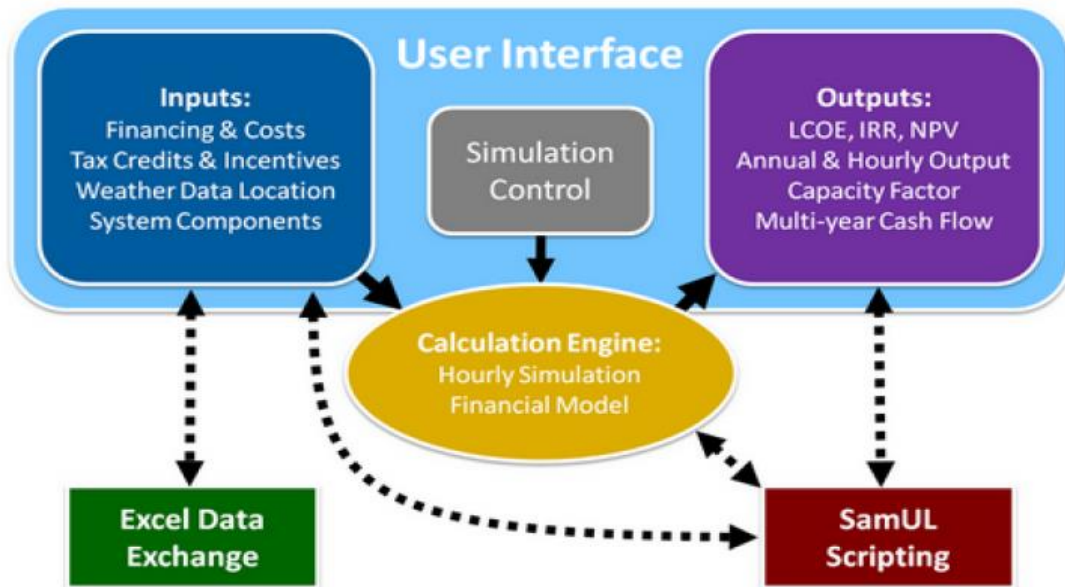


Figure 56: Structure diagram of SAM tool [132].

In order to run simulations in SAM, the software requires certain user inputs i.e. weather data, finance and technical. The required weather data consists of the climate or weather data of the project's site. The required finance data feeds a financial scenario for the project for example loan period, interest rates, discount rates, land costs and transactions costs etc. Moreover, the required technical data inputs are the ones to define the project's

technology type i.e. CSP or PV etc, project's size, shading parameters or storage durations etc. Figure 56 illustrates the overview of the SAM inner working structure. Figure 57 is a screenshot of the SAM main window showing monthly electricity generation and the annual cash flow for a photovoltaic system.

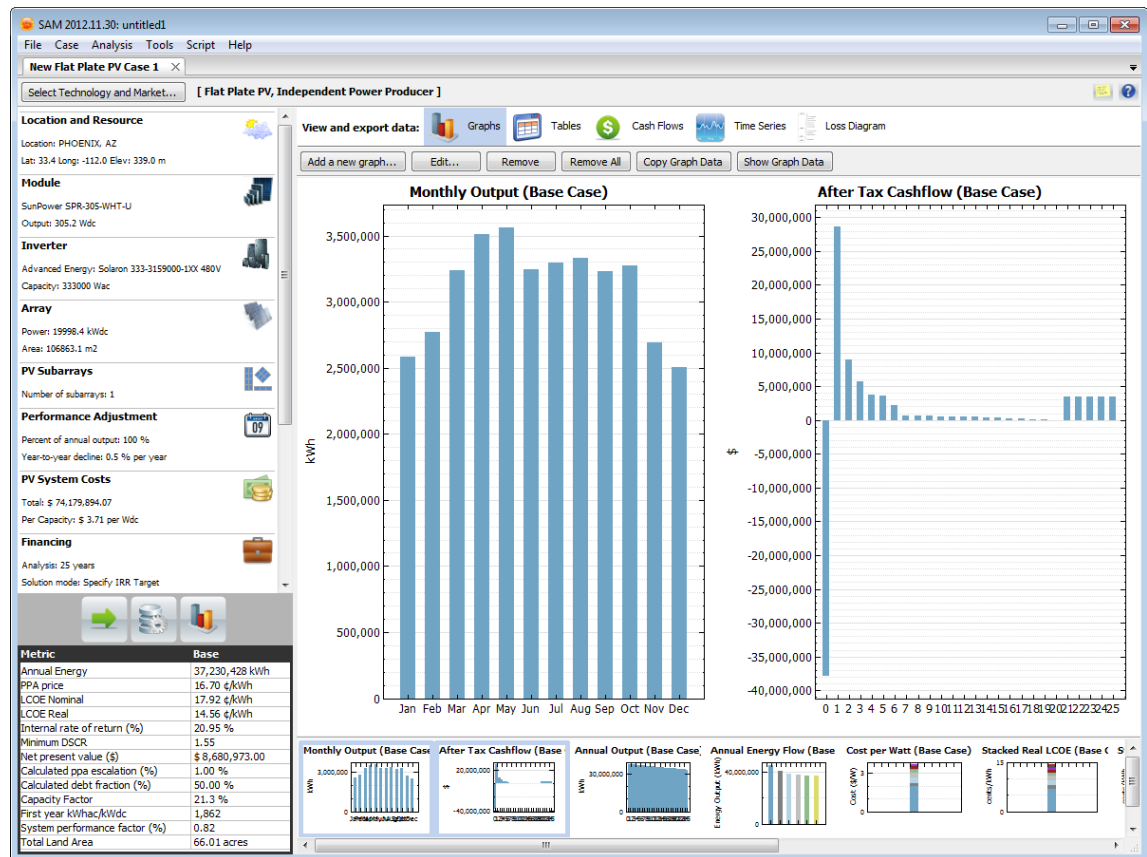


Figure 57: The SAM main window showing monthly electricity generation and the annual cash flow for a photovoltaic system.

SAM includes several libraries of performance data and coefficients that describe the characteristics of system components such as photovoltaic modules and inverters, parabolic trough receivers and collectors, wind turbines, and CSP systems. For those components, you simply choose an option from a list, and SAM applies values from the library to the input variables.

Once satisfied with the input variable values, simulations can be run. A typical analysis involves running simulations, examining results, revising inputs, and repeating that process until satisfactory results are produced. SAM displays modelling results in tables and graphs, ranging from the metrics table that displays levelized cost of energy, first year annual production, and other single-value metrics, to tables and graphs that show detailed annual cash flows and hourly performance data. Figure 58 illustrates an example screenshot of the graphs on the results page which are showing hourly electricity generation for a 100 MW parabolic trough system with 6 hours of storage.

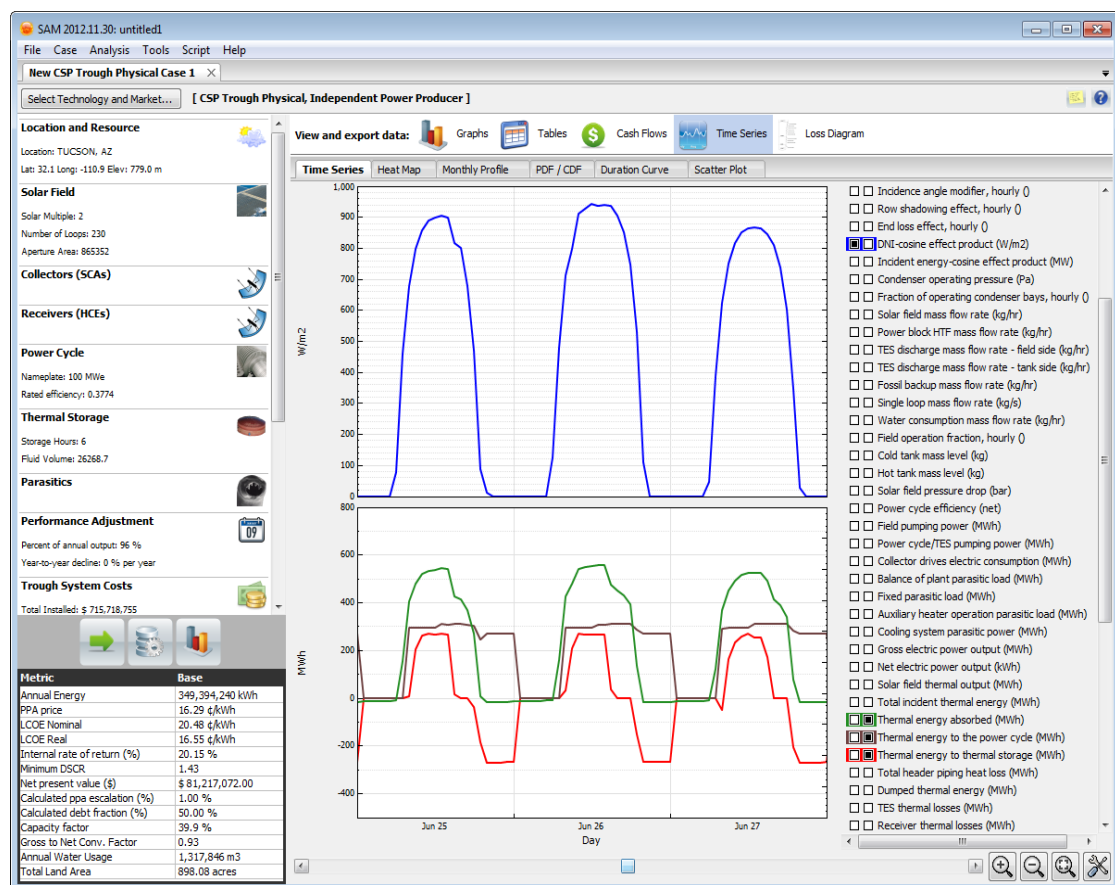


Figure 58: The Time Series graph on the results page showing hourly electricity generation for a 100 MW parabolic trough system with 6 hours of storage.

SAM's performance models make hour-by-hour calculations of a power system's electric output, generating a set of 8,760 hourly values that represent the system's electricity production over a single year. One can explore the system's performance characteristics in detail by viewing tables and graphs of the hourly and monthly performance data, or use performance metrics such as the system's total annual output and capacity factor for more general performance evaluations.

The current version (released in 15th of Jan 2013) of the SAM includes performance models for the following technologies:

- Photovoltaic systems (flat-plate and concentrating)
- Parabolic trough concentrating solar power
- Power tower concentrating solar power (molten salt and direct steam)
- Linear Fresnel concentrating solar power
- Dish-Stirling concentrating solar power
- Conventional thermal
- Solar water heating for residential or commercial buildings
- Large and small wind power
- Geothermal power and geothermal co-production
- Biomass power

SAM's financial model calculates financial metrics for various kinds of power projects based on a project's cash flows over an analysis period that you specify. The financial model uses the system's electrical output calculated by the performance model to calculate the series of annual cash flows. SAM includes financial models for the following kinds of projects:

- Residential (retail electricity rates)
- Commercial (retail rates or power purchase agreement)
- Utility-scale (power purchase agreement)
- Single owner

Residential and commercial projects are financed through either a loan or cash payment, and recover investment costs by selling electricity through either a net metering or time-of-use pricing agreement. For these projects, SAM reports the following financial metrics:

- Levelized cost of energy
- Revenue with and without renewable energy system
- After-tax net present value
- Payback Period

SAM calculates the levelized cost of energy (LCOE) after-tax cash flows for projects using retail electricity rates, and from the revenue cash flow for projects selling electricity under a power purchase agreement.

The project annual cash flows include:

- Revenues from electricity sales and incentive payments
- Installation costs
- Operating, maintenance, and replacement costs
- Loan principal and interest payments
- Tax benefits and liabilities (accounting for any tax credits for which the project is eligible)
- Incentive payments
- Project and partner's internal rate of return requirements (for PPA projects)

6.5. Simulations for Wind, PV and CSP for study case of Cyprus

6.5.1. Input parameters used as weather data

For this particular study, a weather file in EnergyPlus Weather (EPW) file format was used. This data file is downloaded from the international weather databases of U.S Department of Energy [52]. The site's location is called Larnaca and located at 34.88° N, 33.63° E with GMT +2 hours. The weather file consists of data sets which have been constructed from the years from 1985 to 1995. The details of this dataset were presented as solar and wind data in chapter 2.

The weather data consists of parameter entries such as dry-bulb temperature, dew-point temperature, wet-bulb temperature, relative humidity, wind speed, wind direction, atmospheric pressure, global horizontal radiation, direct normal radiation, direct horizontal radiation, albedo (reflection coefficient), and snow depth. Each of these enlisted entries is used to form and condense to a representative and typical one year profile of 8760hours.

6.5.2. Input parameters used for financial parameters

Financial parameters used in this study are tabulated at figure 59. These parameters will be same for all the RES technologies throughout the analysis. Hence, it will form the consistent and common base for all.

Entry (Units)	Value	Entry (Units)	Value
Analysis Period (years)	30	Loan Term (years)	30
Inflation Rate (%)	3	Loan Rate (%/year)	10
Real Discount Rate (%)	6	Debt Fraction (%)	100
Insurance (%)	1	PPA Escalation Rate (%)	1.5
Total Tax (%)	None	Positive Cash Flow	Yes
Any Incentives	None	Minimum DSCR	1.1 & 1.5
State/Federal Depreciation (%)	None	Cost of Land (\$/acre)	10000

Figure 59: Financial parameters used in the analysis of this study

For this particular study the financial model used is based on the “Utility IPP and Commercial PPA” options from the available models within SAM. The solution mode is selected to be the “Specify IRR Target”. This mode basically allows the user to specify the internal rate of return (IRR) as an input, and SAM uses an iterative search algorithm to find the power purchase bid (PPA) price required to meet the target IRR.

Analysis period is the number of years covered by the analysis. Typically this value is equivalent to the project or investment life. This period determines the number of years in the project cash flow.

Inflation rate is the annual rate of change of costs, typically based on a price index. SAM uses the inflation rate to calculate the value of costs in years two and later of the project cash flow based on values in year one that is specified under the system costs i.e. capital costs and O&M costs.

Real discount rate is a measure of the time value of money expressed as an annual rate. SAM uses the real discount rate to calculate the present value (value in year one) of dollar amounts in the project cash flow over the analysis period and to calculate annualized costs.

The annual insurance rate applies to the total installed cost of the project. SAM treats insurance as an operating cost for each year. The insurance cost in year one of the project cash flow is the insurance rate multiplied by the total installed cost from the System Costs. The first year cost is then increased by inflation in each subsequent year.

Loan term is the number of years required to repay a loan. This value therefore serves different purpose compared to the analysis period value. Loan rate is the annual interest rate for the loan.

Debt fraction is the percentage of the total installed cost to be borrowed. For example, specifying a debt fraction of 25% means that the project borrows 25% of the system costs and hence is a 25/75 debt-equity ratio.

Positive cash flow is a requirement that the annual project cash flow be positive throughout the project life.

PPA escalation rate is an optional escalation rate for the power purchase agreement or bid price. An escalation rate applied to the PPA price in Year One of the cash flow to calculate the electricity sales price in Years two and later.

Minimum required DSCR (debt-service coverage ratio) is the lowest value of the DSCR required for the project to be financially feasible. The DSCR is the ratio of operating income to costs in a given year.

Sensitivity studies were conducted to define an optimal value for both loan term and PPA escalation rate in order to minimize the LCOE. This sensitivity study studied PPA escalation rate from 1% to 3% in 0.5% steps and Loan term from 10 years to 30 years in 5 years steps. The results are show at the figure 60 at below. The graphs are plotted against the loan term of 10 years with PPA escalation rate of 1%. Hence each line is the difference against to this reference point.

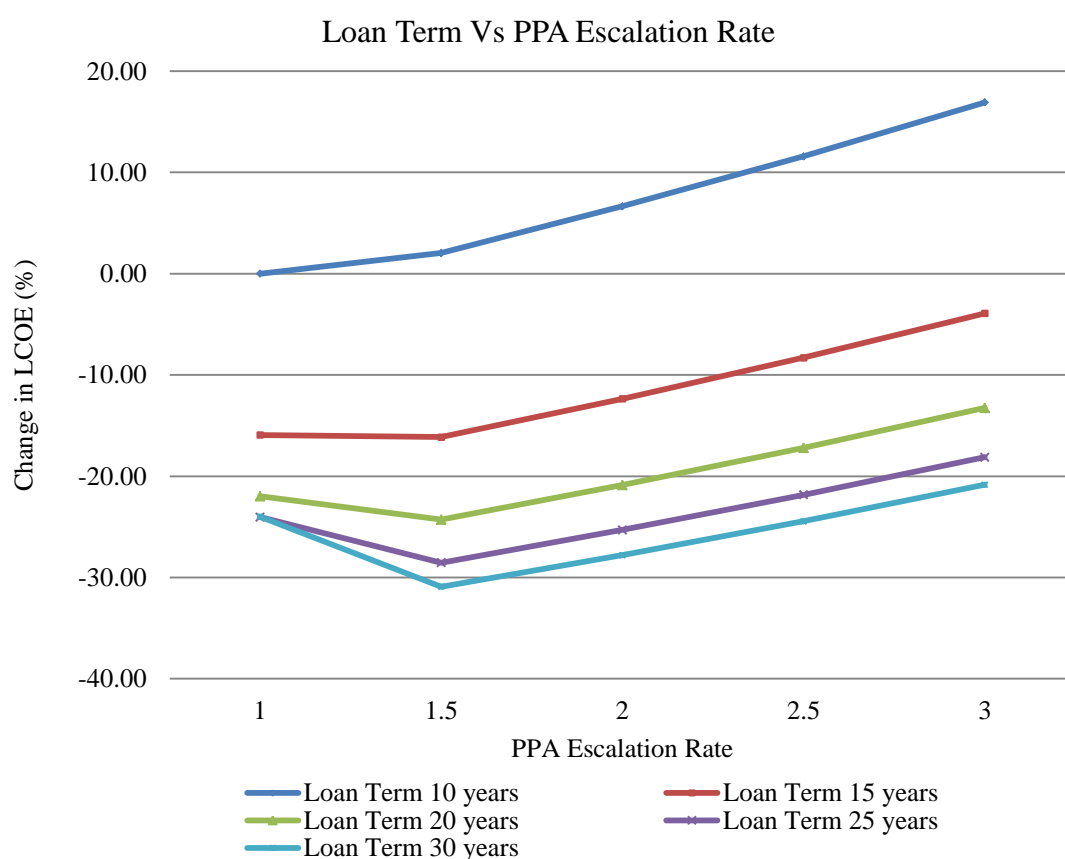


Figure 60: Results of the sensitivity study for defining loan term against escalation rate

Results of the sensitivity study for defining loan term against escalation rate is shown in figure 60. From the figure 60, it can be observed that the choice of loan term of 30 years with PPA escalation rate of 1.5% would reduce the LCOE by at least 30%. Hence these values are chosen to be used in this study.

6.5.3. Parameters used for the technologies

In order to compare different solar technologies, in addition to the parameters set by financial scenario explained in section 5.A, a base for comparing of the power plants in subject has to be used. As mentioned above the sizing of PV plants above 2MW would not make any significant difference on the cost. Among the CSP technologies, Trough systems again will generate the same LCOE cost independent of the capacity size. This will be true for the wind farms as well. On the other hand, CSP tower plant requires being above certain level of size to be mechanically and economically feasible. Hence, the output capacity of tower systems will be further studied and defined.

6.5.3.1. PV and Wind Technologies:

The cost of electricity generated by a PV system is determined by its capital cost, discount rate, variable costs, amount of the solar irradiance and the overall efficiency of the system. Moreover, the capital cost is comprised of the PV modules and the balance of the system (BOS) cost. The BOS cost includes the costs of structural systems, site preparation costs and electrical system costs.

Using the information provided in the section 6.3.2 regarding PV costs, a summary of used values to set up the utility scale PV power plant in subject is shown at figure 62. O&M costs only include scheduled maintenance & cleaning (25\$/kW-year), unscheduled maintenance (2\$/kW-year), inverter replacement reserve (10\$/kW-year). Insurance, property taxes and owner's costs are represented in the finance section as 1% of the total cost.

Plant Size	100MW
Electrical & BOS	4.71 \$/W
PV Modules, Inverter, Design & Admin included.	
O&M Costs	0.037 \$/W-year
System Degradation	1%
System Availability	98%
Post Inverter Derates(AC)	89.97%
Land Packing Factor	2.5
Tracking & Orientation	Fixed, 30°
Shading (Auto Calculate)	Enabled
PV Module	SPR-210-BLK
Inverter	SB8000US-11

Figure 61: PV system's parameters used in the simulations

For the case of simulating a wind system, a real example of Stivo wind farm has been used. The financial information and the every cost of the project were available from the CDM project documents. Using the information from the document the case is set up and the following figure 62 is tabulating the summary of the parameters.

Plant Size	27MW
Electrical & BOS	2.20 \$/W (onshore)
Turbine cost, Foundations & Electrical Infrastructure, Land & System design & Admin	
O&M Costs	0.057 \$/W-year
System Degradation	1%
System Availability	98%
Turbine Spacing	500m
Row Spacing	750m
Offset for Rows	250m
Turbine Layout	Trapezoid: 6 by 3 rows
Turbine	VESTAS V100-1.8
Rated	1800 kW

Figure 62: Wind system's parameters used in the simulations

6.5.3.2. CSP – Tower and trough technologies:

PV technologies, except concentrated PV, can use diffuse or scattered irradiance as well. However, CSP Technologies, unlike PV technologies, require large ($>5 \text{ kWh/m}^2/\text{day}$) direct normal irradiance (DNI) in order to function and be economic. Nevertheless, tracking the sun provides a significantly greater energy yield for a given DNI than a fixed surface and this is one of the main reasons that CSP are tracking the sun.

Compared with conventional power plants, the levelized cost of electricity of CSP plants is formed by the initial investment cost. This investment cost can fulfil almost 80% of the total costs. The remaining 20% is for operation and maintenance costs as well as insurance costs.

In order to enable CSP technologies to store and dispatch energy when the sun is shining, storage means are required. The size of storage and the power block as well as the size of solar field determines the amount of dispatch capacity (in hours). In technical terms, the field aperture area expressed as a multiple of the aperture area required to operate the power cycle at its design capacity is called the solar multiple value. Since the dominant part of the cost of electricity is determined by the solar field, storage and power block, an optimum selection in sizes of these components has to be determined to minimize the LCOE.

Using the SAM software, these parameters are tested for the CSP Tower plant and CSP trough plant. The system is tested with solar multiples from 1 to 3 in 0.5 steps against solar storage hours for each of 24 hours against plant capacity output from 50MW to 250MW with 10MW increments. Therefore for each CSP technology, in order to determine the lowest LCOE with these 3 variables, total of 3150 simulations were run.

The summarized results are shown in figure 63, 64 and 65. According to the simulation results, regarding the lowest LCOE when checked against the CSP tower output capacity, it is at lowest at 130MW. However, as it can be seen from the figure 63, there is a steep decay in LCOE when the output capacity increases from 50MW up until 120MW. From 120MW to 190MW, there is almost a plateau of the level of the LCOE. From 190MW and up, again it can be observed that there is a steep rise to the value of the LCOE. Therefore, the optimum output level at 130MW with a trough from 130 MW to 180MW generates the minimum LCOE for CSP Tower. On the other hand, for the CSP Trough systems, LCOE value is un-affected by the output capacity of the plant.

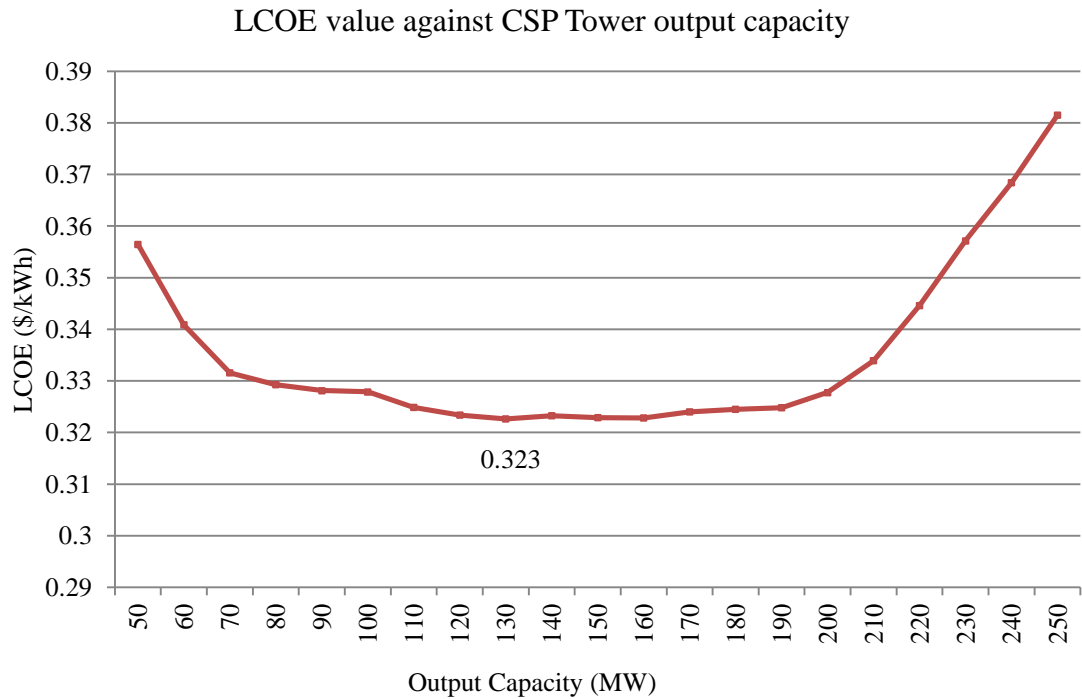


Figure 63: LCOE value against the output capacity of the CSP Tower

In order to determine the lowest LCOE, it is essential to optimize the CSP systems according to the solar multiple and solar storage hours as well. Figure 64 illustrates the results following the simulations of LCOE against thermal storage hours for different solar multiples of the CSP Tower plant. From the figure, it can be observed that there is a parabolic nature of LCOE when increasing the thermal storage hours. On each parabola of the different value of the solar multiple, it can also be observed that there is the minimum LCOE. Among these minimums solar multiple at 2 and thermal storage hours at 4 hours generated the lowest LCOE. However, the LCOE values at the minima points are within 2% of the lowest LCOE except for solar multiple of 1.5 which is 14% away from the lowest LCOE.

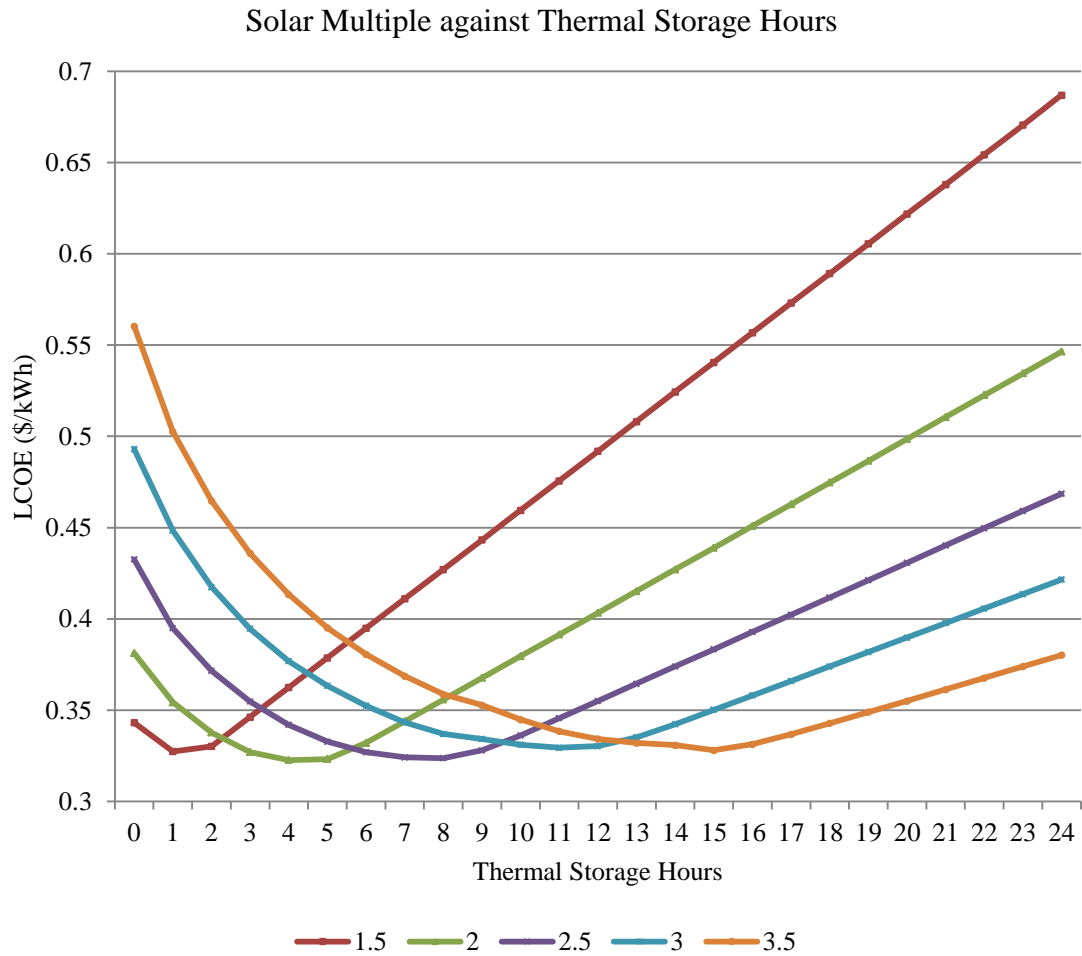


Figure 64: LCOE against thermal storage hours for different solar multiples of CSP tower plant

Figure 65 illustrates the results following the simulations of LCOE against thermal storage hours for different solar multiples of the CSP trough plant. From the figure, it can be observed that there is a linear increase of LCOE when solar thermal storage hours are increasing for solar multiples of 1 and 1.5. On the other hand, there is a parabolic nature of LCOE with the increasing the thermal storage hours for solar multiples of 2 and above. Among the results, solar multiple at 1.5 and thermal storage hours at 1 hours generated the lowest LCOE.

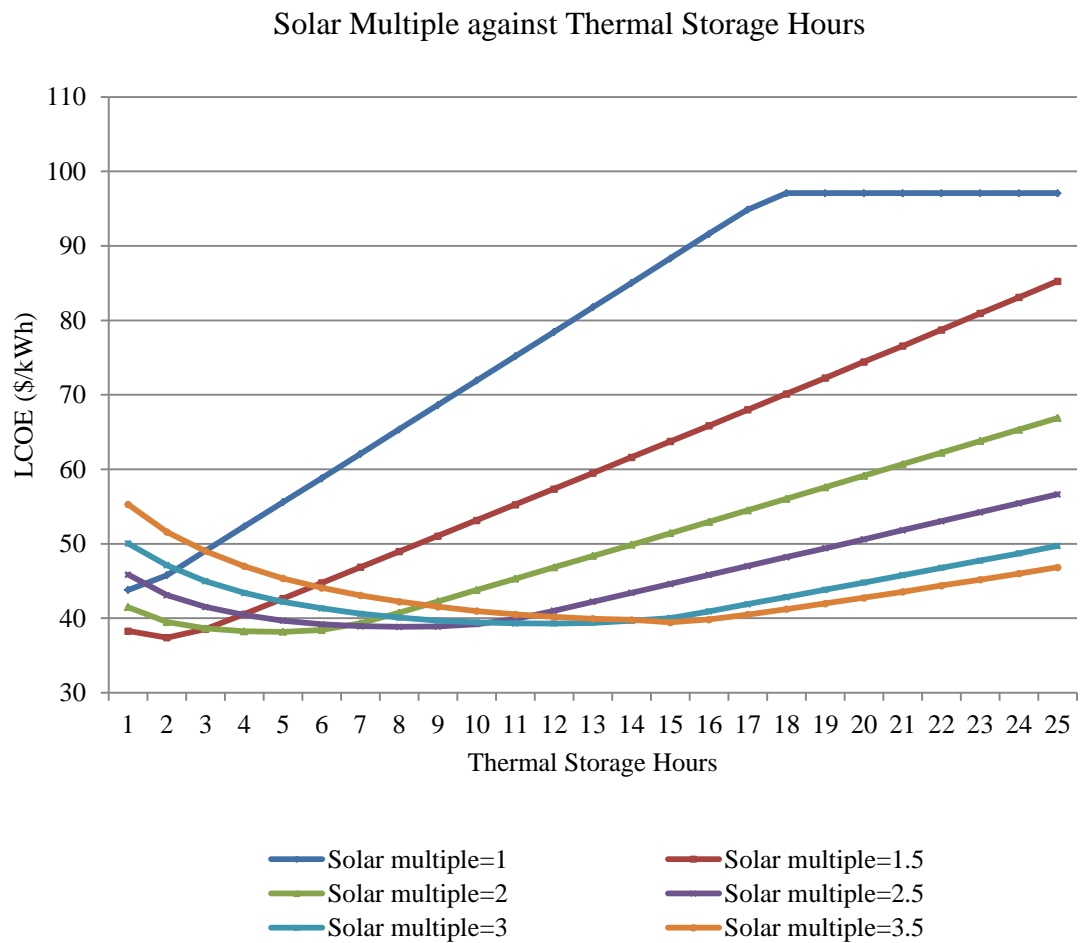


Figure 65: LCOE against thermal storage hours for different solar multiples of CSP trough plant

Following the optimization of the parameters of the CSP technologies with the cost information section 6.3.3, the summary of parameter values used for the simulations are tabulated at figure 66 at below.

PLANT TYPE	TOWER	TROUGH
Plant Size	130MW	50MW
Electrical & BOS	11.77 \$/W	4.49 \$/W
Solar Field	√	√
Power Block	√	√
Storage & HTF systems	√	√
Site prep & Installation	√	√
System design & Admin	√	√
O&M Costs	0.070 \$/W-year	0.070 \$/W-year
System Degradation	1%	1%
System Availability	98%	98%
Storage Capacity	4 hrs	1 hrs
Solar Multiple	2	1.5
Dispatch Schedule	Uniform	Uniform
Heliostat Field	optimized	NA

Figure 66: Parameters used for simulating CSP Tower and Trough technologies

6.6. Simulation Results

In this study the software tool called System Advisor Model (SAM) has again been used [132].

The aim of this chapter is to compare the three main solar technologies and wind power against the conventional energy systems of Northern Cyprus based on their Levelized Cost of Energy (LCOE) price and cost of electricity throughout the years.

In following sections, current and future cost of electricity will be estimated. Following that cost of electricity and LCOE of the RES technologies with four different scenarios will be calculated and illustrated.

6.6.1. Current and future cost of electricity of the current electricity system

In order to be able demonstrate the results against the current electricity system, the trend of electricity price of the KIBTEK since 1995 until today has been extrapolated throughout the years of 2013 to 2042. The function used to extrapolate the electricity price of KIBTEK has R^2 of 0.982.

In regression, the R^2 , coefficient of determination is a statistical measure of how well the regression line approximates the real data points. The coefficient of determination ranges from 0 to 1. A R^2 of 1 indicates that the regression line perfectly fits the data [195].

The used function is $0.0003x^2 - 0.0016x + 0.0103$ where x represents corresponding year. The case, which this function is used, is called “Scenario – Parabolic” which represents the most probable and highest rise in cost of electricity. It is illustrated in figure 67 at below. In addition to this scenario two more scenarios are also considered in order to demonstrate a sensitivity analysis for different estimates of future electricity costs. The case called “Scenario – Linear Medium” represent a linear rise in cost of electricity production with a rise rate of 0.005\$/kWh per year. The case called “Scenario – Linear Low” represents a linear rise in cost of electricity with a rise rate of 0.0025\$/kWh per year.

Figure 67 at below, shows the cost of electricity of KIBTEK from year 2013 to 2042 plotted with these three scenarios.

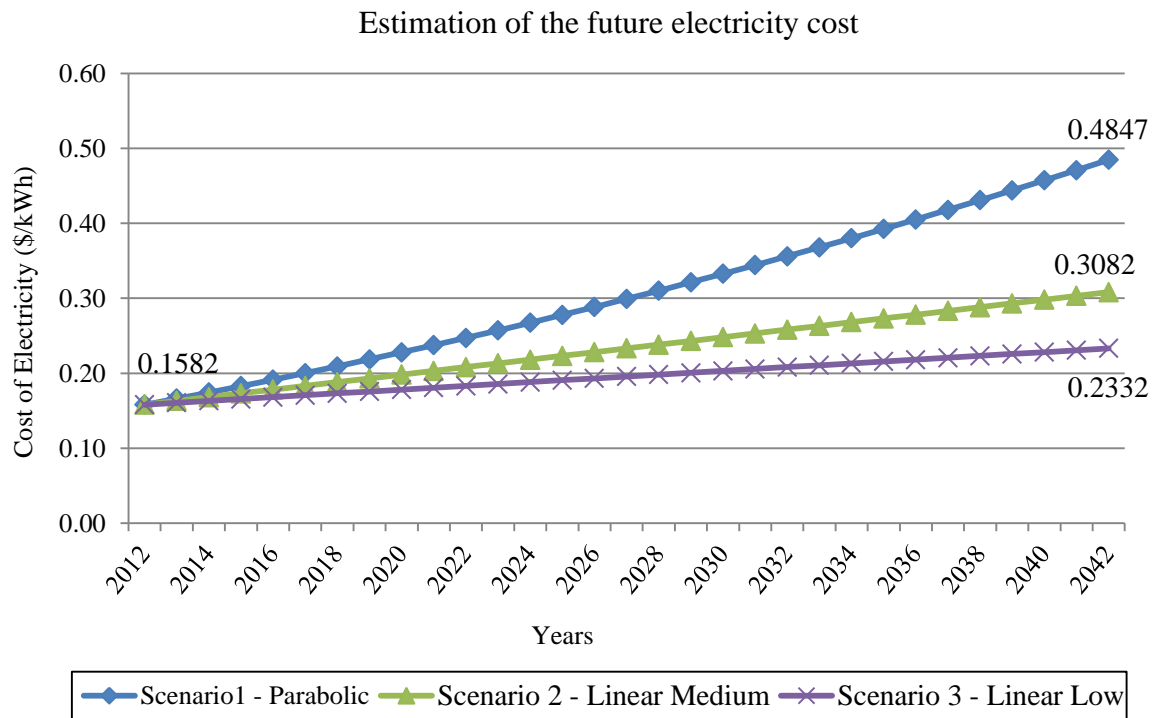


Figure 67: Predicted price of electricity by each RES technology for future years

From the figure 67, it can be observed that the certainty of cost of electricity diminishes when the cost is estimated further into the future years. The cost of electricity is \$0.16/kWh in year 2012 and it is estimated to be between \$0.23/kWh to \$0.48/kWh by the year 2042.

It should also be noted that the term “cost of electricity” is the cost incurred to produce electricity by the conventional generators which includes fuel costs, operational and maintenance costs. It is approximately 60% of the “electricity selling price” which includes the cost of electricity, transmission & distribution costs, costs of losses, tax etc. and profits. It is payable to the electricity authority i.e. KIBTEK.

6.6.2. Scenario of 2013 with DSCR at 1.5

In this scenario, the parameters tabulated in chapter 6.5 are used. The DSCR value is chosen at 1.5. The scenario calculated the cost of electricity of the RES technologies installed in 2013 and assumes 30 years of operational life. The results are illustrated against the three estimated scenario of cost of electricity of KIBTEK as per illustrated in chapter 6.6.1 in figure 67.

Figure 68 illustrates the results of the simulations. On the basis of LCOE, Wind power has the lowest cost of approx. 25 cents/kWh compared to CSP tower at 30 cents/kWh, CSP trough plant's at 34 cents/kWh and PV plant at 43 cents/kWh. This significant difference of cost is reflected to the cost of electricity and to the years taken to at least match the cost of electricity of conventional power plant electricity of KIBTEK. In this sense, Wind power takes almost 25 years to match KIBTEK's cost of electricity. On the other hand solar technologies fail to reach a price as low as the KIBTEK's cost of electricity within their operational lifetime of 30 years.

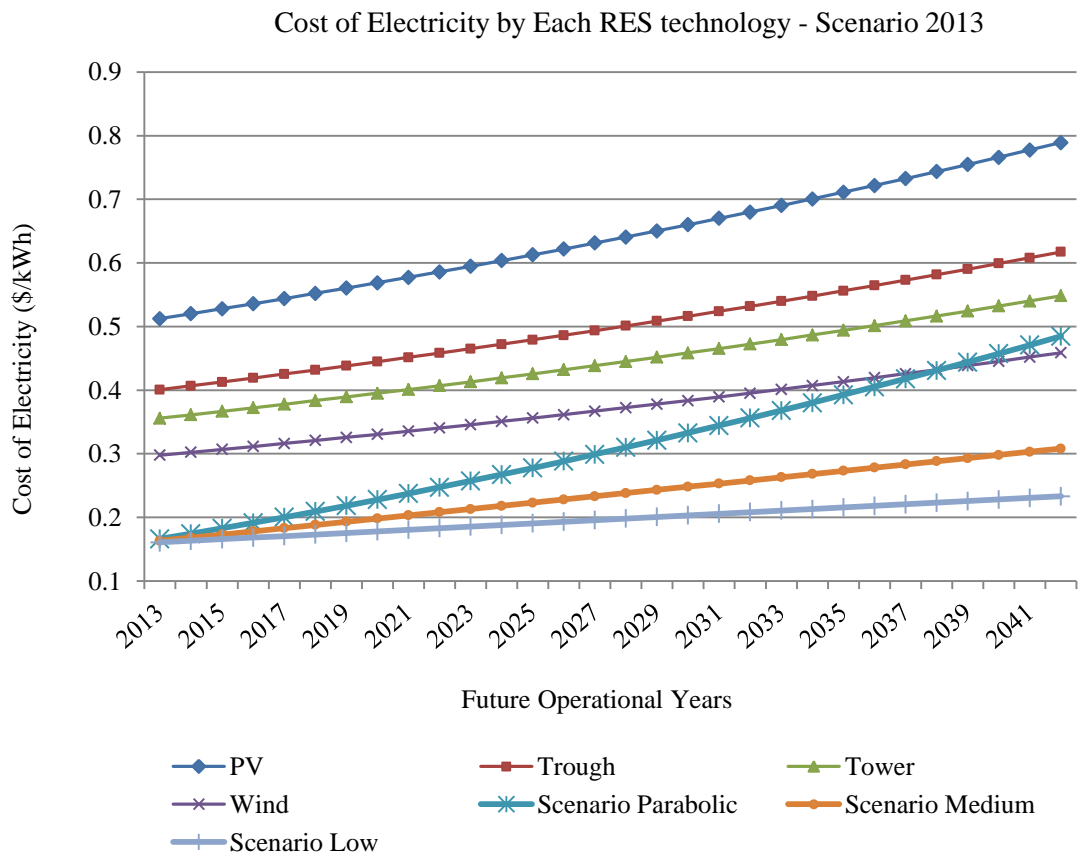


Figure 68: Calculated cost of electricity by each RES technology for future years

Figure 69 tabulates the summary of the financial amounts such as installation cost of the overall project and the net present value of the project.

Power Plant	Installation Cost	Net Present Value	Years*
PV	\$ 237,328,280	\$ 131,824,320	∞
Trough	\$ 194,268,000	\$ 121,195,552	∞
Tower	\$ 599,872,000	\$ 355,858,464	∞
Wind	\$ 59,450,000	\$ 38,135,104	~25

Figure 69: Calculated financial amounts of each RES technology for 2013

Among these technologies, Wind has the minimum land area usage and the lowest LCOE followed by the CSP tower in terms of the LCOE and energy price. The summary of results is tabulated in figure 70.

Installation cost of CSP trough and PV plants almost differs by 20%. However, the land area usage approximately differs by 100%. In that sense PV plant occupies half of the land area used by the CSP trough plant. On the other hand CSP tower plant requires nearly 10 times more land than the PV plant. The amount of land is a function of the solar multiple and CSP tower has a solar multiple of 2 in order to be able to utilize large storage capacity hence the very high requirement for land area.

Power Plant	Installed Capacity (MW)	Land Used (acre)	LCOE (cent/kWh)	Capacity Factor (%)
PV	50	182	43.43	18.70%
Trough	50	340	33.96	21.8
Tower	130	2081	30.17	28.10%
Wind	27	9.4	25.24	17%

Figure 70: Calculated LCOE and few parameter values of each RES technology for 2013

6.6.3. Scenario of 2020 with DSCR at 1.5

In this scenario, the parameters and DSCR value are the same as previous scenario. The difference from the previous scenario is the capital costs of the projects are assumed to be reduced as per the estimated future costs of RES technologies explained in chapter 6.3.

Therefore the projects are assumed to have lower capital costs. Also, since the scenario is looking from 2020, the cost of electricity of conventional generation of KIBTEK has risen by the estimated amounts as per explained in the chapter 6.6.1.

Figure 71 illustrates the results of the simulations. On the basis of LCOE, Wind power has the lowest cost of approx. 14.7 cents/kWh compared to CSP tower at 23.3 cents/kWh, CSP trough plant's at 33.96 cents/kWh and 27.46 cents/kWh of PV plant.

In year 2020, Wind power is almost as low as the “Scenario –Linear Low” of cost of electricity of conventional generators. It is almost \$0.05/kWh lower than the “Scenario – Parabolic”. On this occasion, CSP Tower manages to match the cost of electricity of conventional generators after 8 years and remaining solar technologies after 17 years of operation.

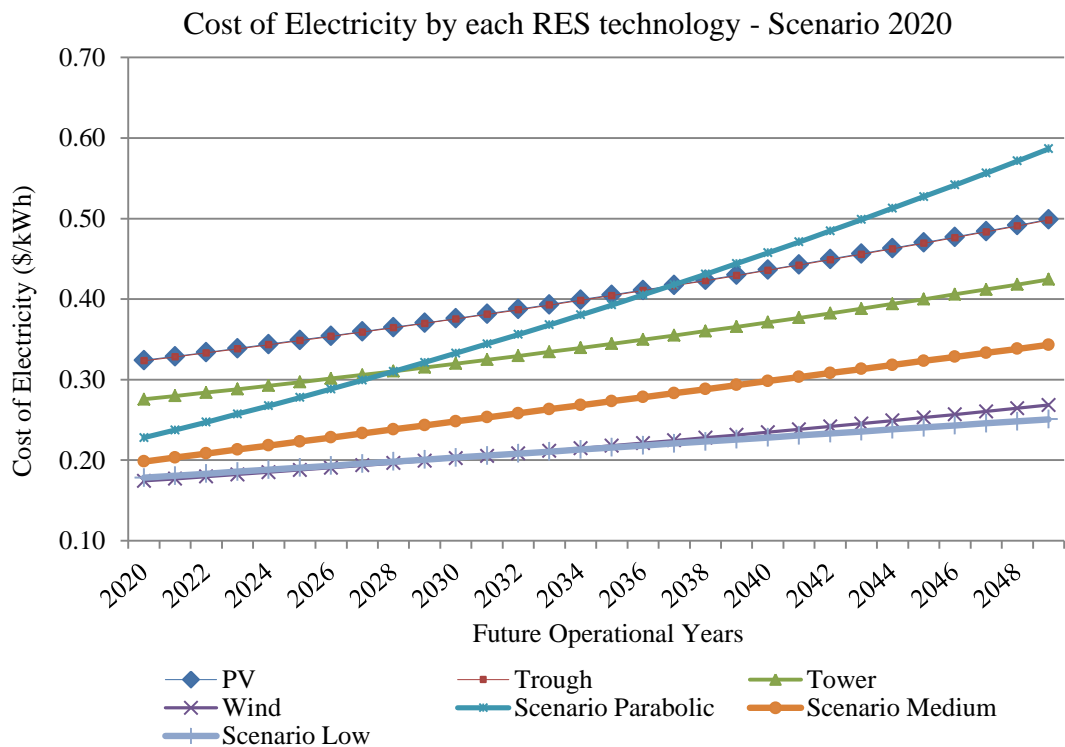


Figure 71: Calculated cost of electricity by each RES technology for future years

Figure 72 tabulates the summary of the financial amounts such as installation cost of the overall project and the net present value of the project. By comparing figure 69 with figure 72, the reduction at installation costs per technology can be observed for year 2013 and year 2020.

Power Plant	Installation Cost	Net Present Value	Years*
PV	\$ 143,328,402	\$ 82,358,472	~17
Trough	\$ 157,819,605	\$ 97,493,720	~17
Tower	\$ 478,932,142	\$ 273,005,024	~8
Wind	\$ 42,768,000	\$ 25,298,690	~0

Figure 72: Calculated financial amounts of each RES technology for 2020.

There are no changes in the terms of land area usage and capacity factor as they are not dependent on project finances. It can again be observed that wind technologies have the lowest LCOE followed by the CSP tower in terms of the LCOE and energy price. The summary of results is tabulated in figure 73.

Power Plant	Installed Capacity (MW)	Land Used (acre)	LCOE (cent/kWh)	Capacity Factor (%)
PV	50	182	27.46	18.70%
Trough	50	340	33.96	21.8
Tower	130	2081	23.35	28.10%
Wind	27	9.4	14.77	17%

Figure 73: Calculated LCOE and few parameter values of each RES technology for 2020.

6.6.4. Scenario of 2013 with DSCR at 1.1

This scenario is looking into implementing the RES projects in year 2013. This time the financial parameter DSCR of 1.1 is assumed instead of 1.5. Therefore the projects are assumed to have same capital costs as per the scenario of chapter 6.6.2. However, the net financial return from the project is lowered by reducing the amount of DSCR to 1.1.

Figure 74 illustrates the results of the simulations. On the basis of LCOE, Wind power has the lowest cost of approx. 20.6 cents/kWh compared to CSP tower at 24.31 cents/kWh, CSP trough plant's at 27.6 cents/kWh and 33.8 cents/kWh of PV plant.

The analysis has demonstrated that it will take 14 years for a Wind technology to match the cost of electricity of conventional generators. CSP Tower manages to match the cost of electricity of conventional generators after 23 years. On the other hand remaining solar technologies fail to reach a price as low as the KIBTEK's cost of electricity within their operational lifetime of 30 years.

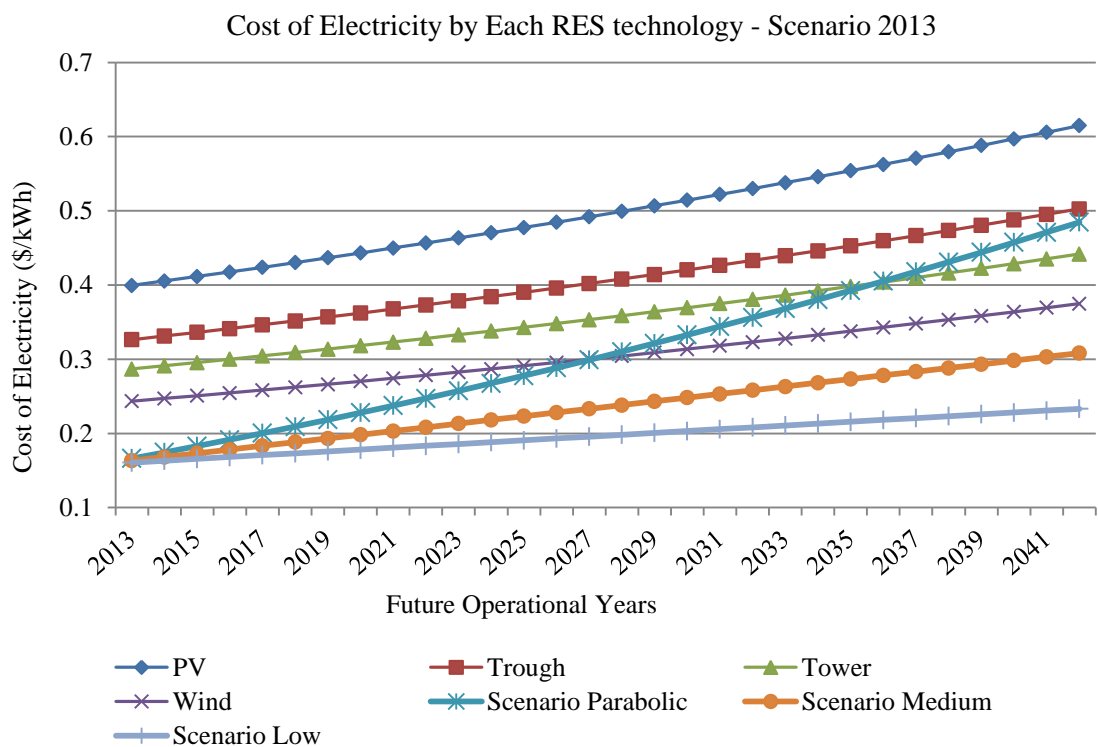


Figure 74: Calculated cost of electricity by each RES technology for future years

Figure 75 tabulates the summary of the financial amounts such as installation cost of the overall project and the net present value of the project. By comparing figure 69 with figure 72, the decrease in the net present values of the projects can be observed due to the lower DSCR value.

Power Plant	Installation Cost	Net Present Value	Years*
PV	\$ 237,328,280	\$ 34,080,928	∞
Trough	\$ 194,268,000	\$ 45,637,752	∞
Tower	\$ 599,872,000	\$ 122,566,520	~23
Wind	\$ 59,450,000	\$ 15,011,435	~14

Figure 75: Calculated financial amounts of each RES technology for 2013.

There are no changes in the terms of land area usage and capacity factor as they are not dependent on project finances. It can again be observed that wind technologies have the lowest LCOE followed by the CSP tower in terms of the LCOE and energy price. The summary of results is tabulated in figure 76.

Power Plant	Installed Capacity (MW)	Land Used (acre)	LCOE (cent/kWh)	Capacity Factor (%)
PV	50	182	33.84	18.70%
Trough	50	340	27.61	21.8
Tower	130	2081	24.31	28.10%
Wind	27	9.4	20.63	17%

Figure 76: Calculated LCOE and few parameter values of each RES technology for 2013.

6.6.5. Scenario of 2020 with DSCR at 1.1

This scenario is looking into implementing the RES projects in year 2020. This time the financial parameter DSCR of 1.1 is assumed instead of 1.5.

Therefore the projects are assumed to cost lower capital costs as well as cost of electricity of conventional generation of KIBTEK has risen by the estimated amounts as per explained in the chapter 6.6.1. As well as, the net financial return from the project is lowered by reducing the amount of DSCR to 1.1.

Figure 77 illustrates and figure 79 tabulates the results of the simulations. On the basis of LCOE, Wind power has the lowest cost of approx. 10.95 cents/kWh compared to CSP tower at 18.68 cents/kWh, CSP trough plant's at 22.28 cents/kWh and 21.99 cents/kWh of PV plant.

It has taken approx. 5.5 years for PV and CSP Trough technologies to match the cost of electricity of conventional generators. Wind technologies on the other hand is almost \$0.05/kWh lower than the scenario-low costs of KIBTEK whereas CSP-tower is lower than “Scenario- Parabolic” and very similar to the “Scenario- Linear Medium” of estimated conventional generators’ cost of electricity.

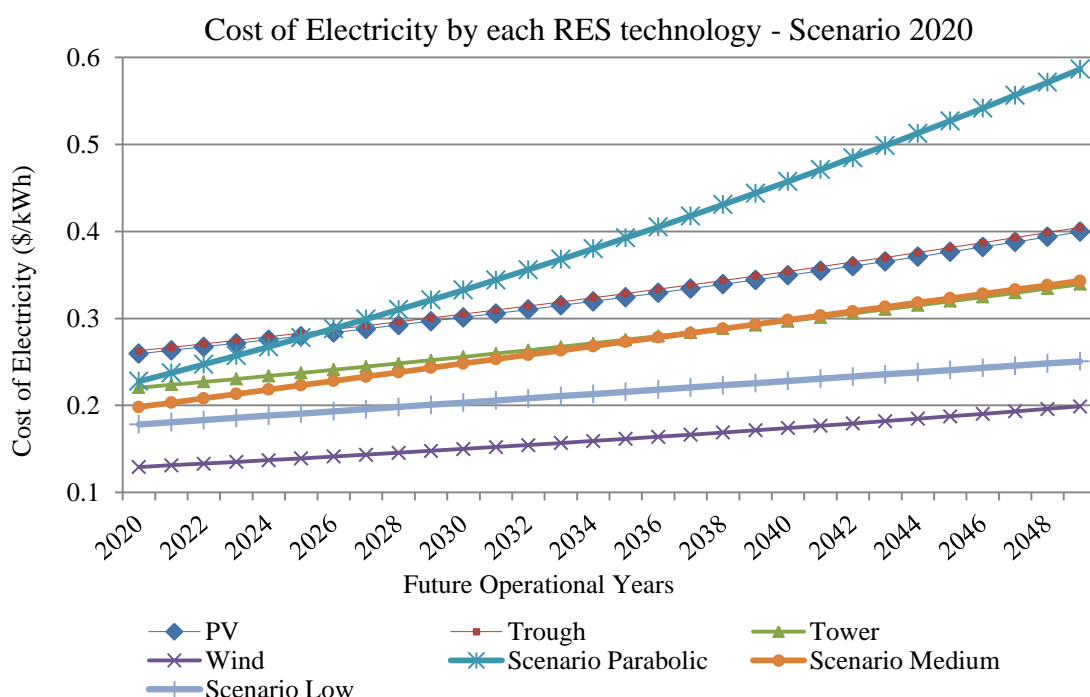


Figure 77: Calculated cost of electricity by each RES technology for future years

Figure 78 tabulates the summary of the financial amounts such as installation cost of the overall project and the net present value of the project. By comparing figure 69 with figure 72, the decrease in the net present values of the projects can be observed due to the lower DSCR value as well as the reduced installation cost can be observed from year 2013 to year 2020.

Power Plant	Installation Cost	Net Present Value	Years*
PV	\$ 143,328,402	\$ 26,610,336	~5.5
Trough	\$ 157,819,605	\$ 36,108,112	~5.5
Tower	\$ 478,932,142	\$ 86,714,056	~0
Wind	\$ 42,768,000	\$ 6,157,081	~0

Figure 78: Calculated financial amounts of each RES technology for 2020.

Power Plant	Installed Capacity (MW)	Land Used (acre)	LCOE (cent/kWh)	Capacity Factor (%)
PV	50	182	21.99	18.70%
Trough	50	340	22.28	21.8
Tower	130	2081	18.68	28.10%
Wind	27	9.4	10.95	17%

Figure 79: Calculated LCOE and few parameter values of each RES technology for 2020.

6.6.6. Estimated GHG reductions

The abundance of solar energy in Cyprus offers an ideal opportunity for the generation of electricity to meet the growing electricity requirements as well as reducing CO₂ emissions. The principal technologies for providing utility scale power generation are wind, PV, and concentrating solar power, CSP, plants.

Integrating solar power plants using these technologies into the Cyprus power system has the advantage of matching the summer peak in demand. However, wind power has the lowest energy prices.

In this study the software tool called System Advisor Model (SAM) has been used [132].

In this study three main solar technologies and wind power has been compared against the conventional energy systems of Northern Cyprus based on their Levelized Cost of Energy (LCOE), installation cost, land area used and selling electricity price throughout the years.

In order to calculate the theoretical reductions in green house gas (GHG) emissions pre-defined methodology provided by the UNFCCC can be used. This methodological tool determines the CO₂ emission factor for the displacement of electricity generated by power plants in an electricity system, by calculating the combined margin emission factor (CM) of the electricity system. The CM is the result of a weighted average of two emission factors pertaining to the electricity system: the operating margin (OM) and the build margin (BM).

The operating margin is the emission factor that refers to the group of existing power plants whose current electricity generation would be affected by the proposed CDM project activity. The build margin is the emission factor that refers to the group of prospective

power plants whose construction and future operation would be affected by the proposed CDM project activity. The tool and its details are available from UNFCCC [193].

From the figure 20, combined margin (CM) can be easily deduced by dividing the estimated annual GHG reductions by the calculated annual production. The summary is tabulated at figure 80. It can be seen that the value is between 0.77 and 0.82 averaging at the value of 0.78.

Wind Farm	KAMBI	STIVO	KLAVDIA	AGIA-ANNA	ALEXI_GROS	ORITES	MARI
Calculated Annual Production	15,726 MWh	39,385 MWh	59,580 MWh	30,860 MWh	76,002 MWh	213,920 MWh	21,219 MWh
Estimated annual tCO₂ reductions	12,864 tonnes	30,399 tonnes	45,884 tonnes	23,778 tonnes	58,427 tonnes	174,990 tonnes	16,313 tonnes
Combined Margin (tCO₂/MWh)	0.81	0.77	0.77	0.77	0.77	0.82	0.77

Figure 80: Combined margin of the wind projects of South Cyprus.

Therefore, CM value of 0.78 can be used in order to estimate the GHG reduction of the studied RES technologies. Figure 81 tabulates these technologies with their calculated annual production and estimated GHG reductions.

	WIND	CSP TOWER	CSP TROUGH	PV
Output Capacity	27MW	130MW	50MW	50MW
Load Factor	17.0%	28.1%	21.8%	18.7%
Calculated Annual Production	40,278 MWh	319,877 MWh	96,091 MWh	81,927 MWh
Estimated annual tCO₂ reductions	31,416 tonnes	249,504 tonnes	74,950 tonnes	63,903 tonnes
Estimated annual tCO₂ reduction per installed capacity	1,163 tonnes/MW	1,919 tonnes/MW	1,499 tonnes/MW	1,278 tonnes/MW

Figure 81: Estimated annual reductions of GHG of RES technologies

Since the CM value is a constant applicable for all RES technologies, the estimated reduction of GHG emissions will be directly related to the annual production of the RES technology. However, in the terms of estimated annual GHG emissions reduction per installed capacity, the amount is directly related with the capacity factor of the RES technology. Hence, CSP tower has the highest reduction in emissions as much as 1,919 tonnes per installed MW per year with the highest load factor of 28.1% whereas wind power has the lowest capacity factor of 17.0% with lowest GHG emission reduction of 1,163 tonnes per installed MW per year.

6.6.7. Load curve with superimposed RES technologies

In order to be able to demonstrate the effect on the demand curve by using RES technologies along with conventional generators, the daily electricity curve with and without the RES contribution has to be illustrated. For demonstration purposes only three typical days of the year from January, July and November are chosen.

These days are representing a typical day of that corresponding month without any extremes. The capacity of each RES technology is as per used in the previous sections of chapter 6.

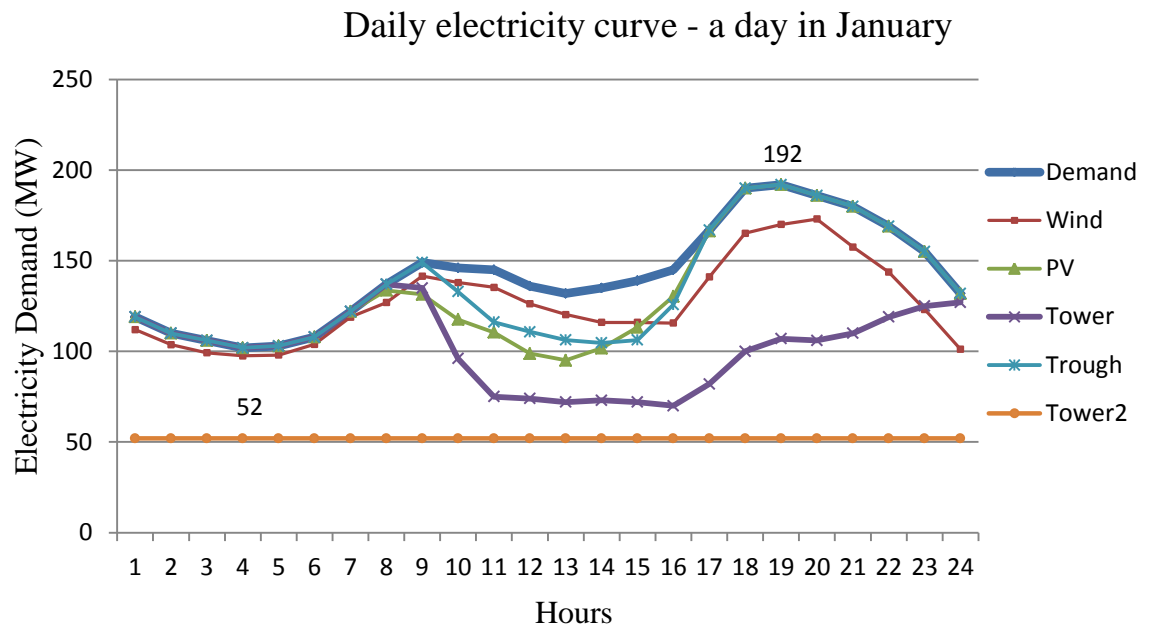


Figure 82: Daily electricity curve with and without RES contribution in January

Figure 82 illustrates the contribution of wind technology offsetting some of the output of the conventional generation. This is a typical day in January. The demand pick up started from 6 a.m. and morning peak reached by 10 a.m. in the morning. The demand stays as a plateau until 17:00 hrs and then peaks for the evening 18-19:00 hrs. Following the peak, demand decays until 4-5 a.m. know as day minimum.

From figure 82 it can be observed that wind energy is offsetting the conventional generation throughout the day. The amount of offset increases starting from the afternoon to the midnight. PV on the other hand starts offsetting the conventional generation from the sun rise until the sun set. The overall impact is the plateau demand from morning to late afternoon is reduced and troughed. The evening peak remained the same. Compared to PV, CSP plants start to produce electricity after couple of hours of delay due the requirements of steam boilers and storage facilities. CSP trough has rather a short storage capacity and hence demonstrates similar behaviour with the PV.

However, CSP tower, due to its size and long storage capacity, is able to offset large amount of conventional generation starting from morning until late night time and can vary its output according to the operator needs. Two different cases of CSP Tower is calculated and illustrated in figure 82, 83 and 84. The case called “Tower” is demonstrating a case in which storage capacity is actively used to store and dispatch energy maximizing the instantaneous output when sun is shining. On the other hand the case called “Tower2” illustrates one of the biggest advantages of the CSP storage which is the use of storage to offset the conventional generation by following the demand curve and offsetting the conventional generation to a fixed level. The difference between “Tower” and “Tower2” is that “Tower2” has greater storage capacity of 6hrs instead of 4hrs. The output capacity for both systems is 130MW.

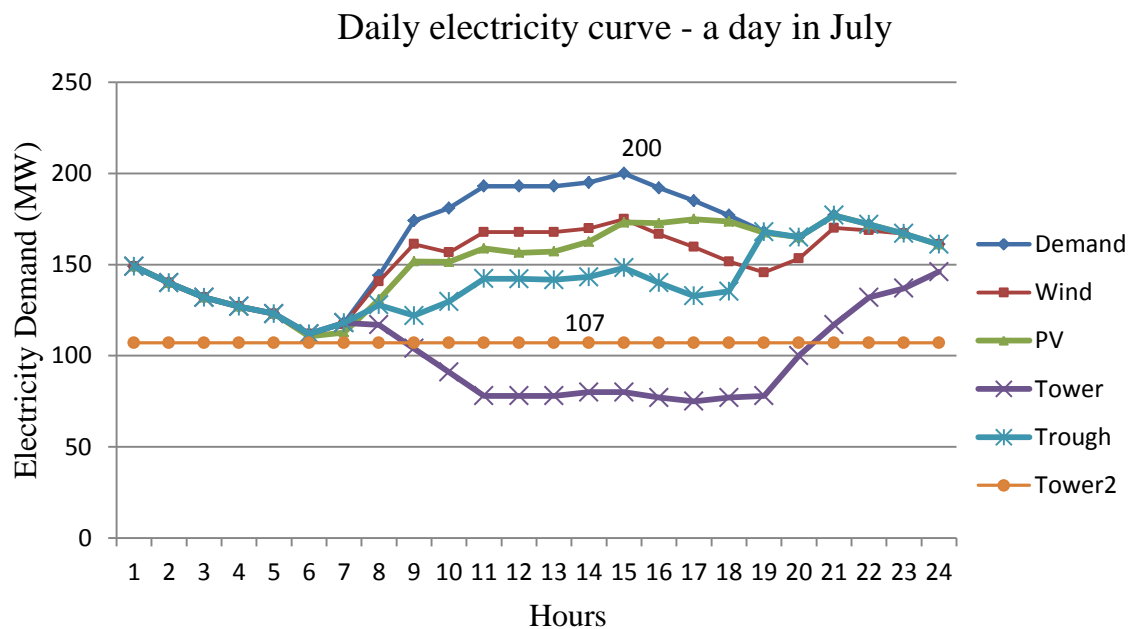


Figure 83: Daily electricity curve with and without RES contribution in July

The resultant fixed level of conventional generation means that conventional generation can run as base load units and solar CSP able to vary its output with use of its storage capabilities and follow the demand curve. Therefore by fully utilizing storage capabilities of such system from figure 82, the daily peak demand no longer exists and it is reduced from 200MW to 107MW. On the other hand, the daily peak demand is reduced from 152MW to 51MW in November and 192MW to 52MW in January as illustrated in figure 83 and figure 84. An immediate advantage of this load profile smoothing is that the operators can make best use of the base load generation, namely fuel oil, and avoid using the faster response diesel generation.

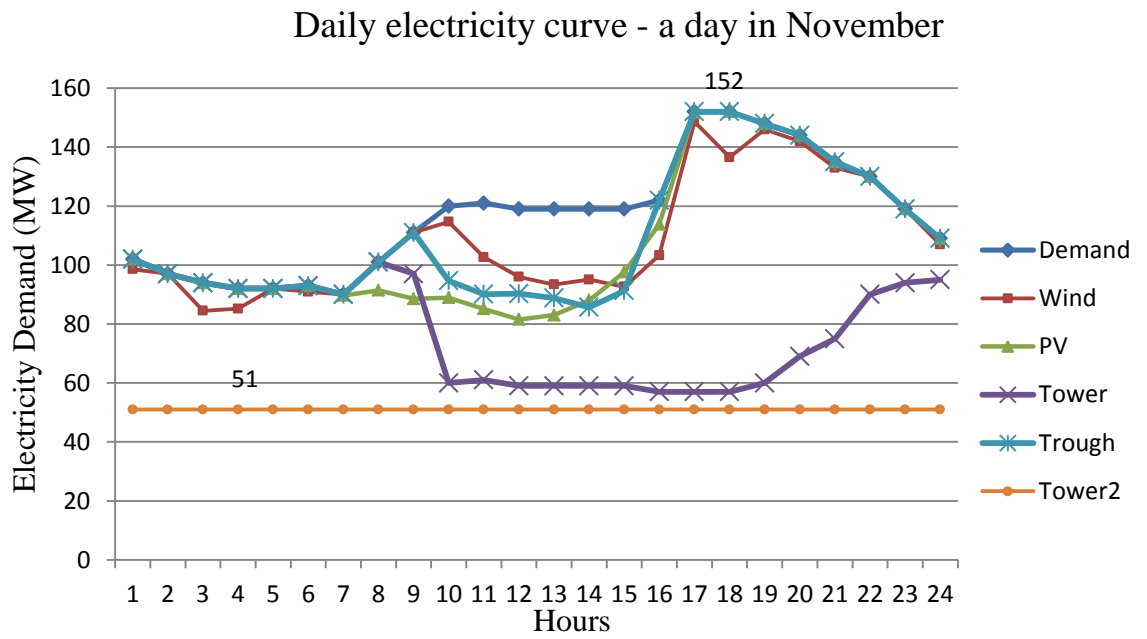


Figure 84: Daily electricity curve with and without RES contribution in November

CHAPTER 7

CONCLUSIONS

This chapter collates the findings and results of the project, summarizes the contributions and introduces topics which would be areas for further research

7. Conclusions and future work

7.1. Summary of results and findings

Currently Cyprus is almost entirely dependent on fossil fuel imports for its energy. In 2007, imports of oil products, coal and pet coke amounted to 1.05 million Euros, representing 16.7 per cent of the country's domestic imports. Energy is therefore of vital importance to the Cyprus economy. Energy consumption is predominantly oil-based and amounts to 96 per cent of the total consumption.

Within the present Cypriot electricity generating system, steam turbine units have a range of efficiencies from 25 to 36 per cent, gas turbines from 18 to 26 per cent, combined cycles and diesel engines between 40 to 45 per cent, averaging an overall efficiency of power generation since 2006 of 36 per cent.

In 2011, the published data of the European Environment Agency (EEA) regarding the CO₂ generated electricity per kilowatt hour in 2009 per member country indicated that Cyprus is one of the highest emissions producers with a 0.67 kg per kWh.

In South Cyprus domestic demand represents 36 per cent of total electricity consumption compared with 32 per cent in Northern Cyprus. Forty-one per cent of the domestic electricity consumption is used for space heating, space cooling and water heating.

There are published studies on the use of insulation and its impact on the walls, floors and roofs of buildings. The studies show that the use of 50mm roof insulation would gain as much as a 19 per cent saving in energy for heating and as much as 46 per cent for cooling.

As regards heat insulation measures, presently, only 43.2 per cent of houses have double glazing, while just 7.5 per cent use heat insulation on walls and 5.5 per cent for roofs. All of these offer opportunities for improvement and subsequent energy savings.

From the various studies and trends in electricity demand since 1997, the indication is that the demand for electricity will increase year-on-year if no changes were introduced. This increase compared with the electricity demand in 2010 could range from 33 to 46 per cent for Northern Cyprus and 36 to 53 per cent for the South Cyprus until 2020.

Objectives to develop RES and reduce CO₂ emissions were introduced by the European Commission in the European Climate Change Program (ECCP). The target for Cyprus was to achieve a 6 per cent share of renewable energy in electricity production by 2010. It achieved 4.3 per cent. As part of the Community targets for 2020, Cyprus has to achieve a 13 per cent of renewable energy.

With the estimated increase in electricity demand, to achieve these targets and lower the high costs of imported energy, a burden on the economy, there needs to be a major investment in generation using renewable energy.

Tidal energy potential has been assessed in studies conducted by other writers and it appears that sites with a mean range exceeding 3m can be exploited. None of this potential exists in the Eastern Mediterranean.

Lack of rivers with significant yearly flows also draws a line under hydroelectric opportunities in Cyprus, and neither is there any geothermal resources existent in the island. The potential for small hydro plants is very limited, especially with the water shortages experienced over past years. The suitable sites are estimated as being adequate for a maximum of about 1 MW installed capacity.

Biomass resources in Cyprus include a wide range of agricultural and forest residues, municipal solid waste, sewage water sludge and a considerable potential from energy crops, including traditional herbaceous or short rotation woody, crops. A large energy potential exists from energy crops that can be grown on deforested or otherwise degraded land. Currently eight installations are producing electricity from the anaerobic digestion of animal waste. Their capacity is ~4 MW and the production for 2009 was around ~25 GWh.

In addition, 0.95MW are being constructed and will use the municipal sewage to produce electricity.

Regarding the wind potential in Cyprus, Meteorological services under the Ministry of Agriculture of South Cyprus have compiled a mean annual wind speed map of the island. This compiles the mean annual wind speed (m/s) for the period from 1982 to 1992 and shows that flat areas of the island have a mean wind speed range of 3 to 4 m/s. Areas near the coast have a mean speed range of 4 to 5 m/s.

The possibility of installing wind turbines on the southern coast of Cyprus (near shore applications) is currently being investigated by the government. Initial studies showed that due to the depth of the sea at a relatively short distance from the shore, more than between 30m and 300m from the shore, the cost of installing wind turbines is expected to be very high, to the extent that the wind potential which exists at those areas will not be enough to compensate for the investment.

In order to be able to assess the wind potential of Cyprus, data from a wide spread of sites on the island has been gathered and collated from different publications and also from five years' data from well-established internet-based weather databases. The data comes from sites at the various cities around the island; Paphos, Larnaca, Limassol, Akrotiri, Athalassa, Ercan, Paralimni and Polis. From the data, a theoretical picture of the wind potential at these chosen sites, and the load factors at each site can be calculated. Preliminary results indicated that load factors varied from site to site from 8.4 per cent at Larnaca to 23.85 per cent at Paralimni, with an overall average of 15.1per cent.

Since 2004, twenty five applications for wind parks with a total capacity of approximately 515 MW have been approved by the Cyprus Energy Regulatory Authority (CERA). There are difficulties in starting construction of wind parks because of significant barriers to incorporating wind energy into the Cyprus energy system; to date only a few projects have signed a Connection Agreement with TSO. Only one is operational.

These barriers can be due to the prevailing practice, lack of experience in technology or investment risks. Wind farm projects are one of the “first of this kind” in Cyprus as at present. Despite the fact that projects are approved by the CERA, the final regulations referring to town planning/building laws for wind farms have not been enacted yet and are still being followed as a guiding principle only.

Current electricity production in Cyprus is operated by the electricity authorities. A privately-operated large wind generation system is unknown within the power industry. In terms of operation, the wind farm will be one of the very first commercially operated projects and staffing and knowledge infrastructures regarding construction, operations and maintenance have to start from scratch, leading to increased training costs. In addition, the projects will introduce technology from abroad. All material and even crane facilities to erect the turbines will have to be imported, leading to higher costs.

Barriers to investment are related to perceived risks associated with wind energy in Cyprus where there is no financial experience regarding the implementation and operation of wind farms, and the rather low wind speed pattern known to prevail in Cyprus. It has proved quite difficult to attract investors and also get debt funding. Financial institutions, lacking experience of these types of investments, perceive higher risks associated with the operation and maintenance of the equipment, making it difficult for the project to obtain loans for operations and maintenance.

To overcome these barriers companies are choosing to register the projects under the Clean Development Mechanism (CDM). CDM registration is expected to create an additional income stream from the sale of certified emission reduction (CER), substantially increasing the economic attractiveness of the project. Creation of the additional income stream is expected to help in securing the finance of the project and on better terms than otherwise would have been possible.

Regarding the solar potential of Cyprus, all parts enjoy a very sunny climate. In the central plain and eastern lowlands, the average number of hours of bright sunshine for the year has been measured as 75 per cent of the time that the sun is above the horizon. The periods of sunshine are amongst the longest in the world and the solar intensity is one of the greatest. Using solar technology for power generation, the annual solar potential for properly sited power plants is estimated to be between 1950 kWh/m² and 2050 kWh/m² per year.

In exploiting abundant solar energy, solar thermal heaters have been used extensively. Cyprus has more than double the number of installed solar thermal collectors and produces twice the energy using these systems than the next European user, Austria. The typical solar water system can provide all the necessary hot water that a family of four requires during the four months, June to September; and saves about 360 kWh of electricity.

Solar energy has been heavily exploited in Cyprus for many years, albeit not for bulk electricity generation. To date, solar generation projects have been under commercial or personal use with levels up to 20kW_{peak} with no option to sell electricity to the grid. However, there is no large scale solar to electricity generation project connected to the Cyprus electricity system.

Electricity demand is affected by variables such as relative humidity, cloudiness, solar radiation, wind speed, electricity price, gross domestic product growth, etc. In the most of the electricity systems, the residential sector is one of the main contributors to the load peaks.

Daily demand data from a typical day in summer (July) and winter (December) gathered from the system operators, were analysed. The correlation of the two demand curves at different cardinal points such as summer morning peak, summer noontime plateau and winter darkness peak indicate the similar behavioural patterns of the Northern and Southern demands.

Over the last decade the electric energy consumption in the residential sector has significantly increased, especially in the summer season, because of the increasing use of air-conditioning (AC) systems, which has drastically changed the thermal comfort needs of the urban population in the developed countries. The strong penetration of the AC systems on the market was also quickened by the sudden and rapid reduction of their cost resulting in an increase in the “urban heat island” effect.

This urban heat island effect is further studied. From 2010, a rise in average daily temperature of 1°C from 24°C to 25°C would result in an increase of about 4.2 per cent in electricity consumption. However, the demand seems to be less sensitive to temperature fluctuations in winter, since a fall in mean daily temperature of 1°C from 14°C to 13°C would result in an increase of about 2.1 per cent in electricity consumption. This is mainly attributed to the fact that final consumers can use a variety of energy sources for heating for example gas, diesel oil, etc. and electricity practically only for cooling. Nevertheless, the influence of temperature is minimal at approximately 16.7°C. Hence it is the balance point temperature of the year 2010.

In order to determine the average balance point of Cyprus, each year’s data from 2000 to 2010 has been studied and each year’s balance point temperature has been identified. There have been fluctuations of the balance point temperature of Cyprus throughout these years. Nevertheless, the average balance point temperature throughout these years is 16.9°C.

The amount of radiation at any particular location varies both throughout the year (annually) and throughout the day (diurnally). In order to illustrate the relationship between solar radiation versus the air temperature, the data of solar radiation against air temperature is studied for the year 2005. The study indicated that the temperature peaks at around day 224 whereas solar radiation is at its maximum at around day 176, so there has been shown a lag or delay of around 48 days between the maximum radiation and maximum temperature. This annual lag of temperature behind radiation is a phenomenon called the annual march of temperature. It is a result of the changing relationship between incoming solar radiation and outgoing Earth radiation and the lag exists because it takes time for Earth to heat or cool and for those temperature changes to be transferred to the atmosphere.

Each day, radiation receipt begins at sunrise, reaches its maximum at noon and returns to zero at sunset. Although radiation is greatest at noon, studies indicated that the mean temperature does not reach its maximum until two pm. This is because the radiation received by Earth from sunrise until the afternoon hours exceeds the energy being lost through Earth radiation.

As a result, the relationship between air temperature and electricity demand and the relationship between air temperature and solar irradiation, hence the indirect relationship between solar irradiation and electricity demand, has been identified. Therefore, the predictability of solar radiation and its indirect relationship with the electricity demand enables the system or grid operator to predict the peak demand which is the cause of the solar radiation in the first place.

On the basis that electricity demand is linked to air temperature and air temperature is linked to solar radiation, solar energy is seen as one of the best options to be exploited to provide power to the grid system in matching peak demands in Cyprus.

Highest demand periods occur during the day, with seasonal demand cycle peaking during the summer, which should be correlated with the solar generation output. However, it is not immediately obvious how solar or other renewable generation in this case interact with the overall demand profile as the RES generation achieves increasing levels of penetration, especially non summer time periods when electricity demand is not driven by air conditioning.

Unlike conventional generators, intermittent sources of electricity cannot respond to the variation in normal consumer demand patterns. Rapid fluctuations in output can impose burdens on generators and limit their use. The ability to integrate fluctuating sources is improving, and it is unclear to what extent these short term fluctuations limit the fraction of a system's energy that can be provided by intermittent renewables. There is, however, a rather absolute limit to the economic integration of renewable energy sources such as solar PV or wind, based on the fundamental mismatch of supply and demand. Only so much RES

generation can be integrated into an electrical power system before the supply of energy exceeds the demand. This problem is exacerbated by conventional power systems, which have limited ability to reduce the output of base load generators.

An extensive literature search is conducted to collect the available information on expected problems associated with high penetration levels of grid connected PV. These problems were due to the ramp rates of main line generators, reverse power swings during cloud transients, unacceptable unscheduled tie line flows, frequency control, voltage rise, unacceptable low voltages during false trips and distribution system losses, etc. However, none of the literature was specific to Cyprus or related to each other. Therefore, the exact value of level of upper limit for PV penetration is not defined.

In the terms of wind, it is very important to take account its variability in the right way in the power system. The factors that cause the variability of wind resources are meteorological conditions, daily/seasonal variations of wind speed (monthly, diurnal), specific site and height, and geographic dispersion of wind plant. Depending on the penetration of a power system with variable wind energy, additional indirect costs arise for maintaining system reliability to supply the varying demand, because wind energy will not be able to meet demand at its average capacity factor, but at a generally reduced rate depending on its capacity credit.

In addition, the presence of wind power in a power supply system introduces short-term variability and uncertainty, and therefore requires balancing reserve scheduling and unit commitment. Grid operators need to meet peak demand to certain statistical reliability standards even when wind output falls relative to load. During these periods, which range from minutes to hours, electricity markets need to recruit demand-following units (such as gas, hydro, or storage), which at times of sufficient wind remain idle, so that costs arise essentially for two redundant systems, and for inefficient fuel use during frequent ramping. Thus, wind energy reduces dependence on fuel inputs, but does not eliminate the dependence on short-term balancing capacity and long-term reliable load-carrying capacity.

The impact of wind power on the power supply system is critically dependent on the technology mix in the remainder of the system, because the more flexible and load-following the existing technology, the less peak reserves are needed. It is also dependent on the time characteristics of system procedures (frequency of forecasts, etc.) and local market rules. In general, the higher the wind penetration, the higher the variability in the supply system, and the more long-term reserve and short-term balancing capacity has to be committed. The corresponding cost increases are only partly offset by a smoothing out of wind variability when many turbines are dispersed and interconnected over a wide geographical area, but they are more than offset by reduced fuel and operating cost.

In specific applications, the cost of additional wind power also depends on the relative locations of turbines, load, and existing transmission lines, and on whether sufficient load-carrying reserve exists in the grid or has to be built. As expected, variability costs scatter significantly depending on a large array of parameters. They cannot be derived from capacity credit estimates, since these do not contain any information about to what extent cheap base load and expensive peak load are being displaced by wind.

Considering that Cyprus has been set very ambitious targets regarding the level of penetration of renewable power generation, it can be anticipated that the implementation of multi-megawatt RES generation will cause problems regarding the system operation.

The penetration of renewable energies in the power grids has been increasing in the last couple of years due to successful regulations which have been implemented by the European Countries. Therefore, the experience from these European countries can be used as a basis to amend the current grid code which has no reference to RES technologies and their impact. With the new extended grid code; connection of RES technologies will be well defined and their negative impact will be restricted. In fact, depending on grid requirements, their impact may become positive.

These amendments for the grid code of Cyprus can be the following;

1-Active power control: The Transmission operator should be able to communicate with the RES plant and be able to instruct their output to be curtailed. From the example of other European countries; PV generating plants have to be reduced in predefined steps per minute, under any operating condition and from any working point to a maximum power value (target value) which could correspond also to 100 per cent power reduction, without disconnection of the plant from the network. CSP plants, if they are considered in all respects as renewable generating units, otherwise they have to fulfil requirements set for the conventional generating units. If so, the load reduction can reach values around 40 per cent of the nominal capacity, with the limiting factor the stable operation of the heat exchangers. Wind farms or wind turbines should be capable of limiting the active power production inside a predefined range, its rated capacity according to dispatch order using control mechanisms such as absolute power limitation, ramp rate limitation and delta control.

2-Fault ride trough capability: In the event of network fault, with consequent voltage drop, any RES plant has to remain connected to the grid and to inject a certain amount of short-circuit current into the network; furthermore it shall feed-in the same active power (and to absorb the same or less reactive power) as soon as the fault is cleared.

3-Automatic frequency response: To avoid a risk of unsafe system operation when the frequency rises over a certain value, any RES generator shall have the capability to reduce its power generation when the grid frequency exceeds a pre-set value.

4- Reactive power control: Slow changes in network voltage have to be kept within acceptable limits. In case of operation requirements and on demand by the system operator, any renewable generating unit has to support network voltage by injecting into the Grid the appropriate amount of reactive power, in accordance with Network operators' request.

5- Communications and Notifications: The wind farm controller shall enable ordering of the various types of regulation as total orders which can be given both locally and via remote control and considering lots of wind turbines as just one wind farm. Wind farms or wind generators should be equipped with the prediction system for active power estimation of the next day and notify active power prediction to system operator in advance. Then the predictions should be updated for certain time periods continuously to ensure the reliable market operation of the power system.

Without access to reliable information on the relative costs and benefits of renewable energy technologies it is difficult, if not impossible, for governments to arrive at an accurate assessment of which renewable energy technologies are the most appropriate for their particular circumstances.

The absence of accurate and reliable data on the cost and performance of renewable power generation technologies is therefore a significant barrier to the uptake of these technologies.

In order to create and run a valid analysis, whilst a renewable energy technology is being evaluated in comparison with a conventional technology, analyses of all analysed technologies must be based on comparable characterizations. Similarly, the analysis should be conducted on a relevant and consistent macroeconomic and microeconomic base.

The Levelized Cost of Energy (LCOE) allows alternative technologies to be compared when different scales of operation, different investment and operating time periods, or both, exist. Hence, in this study the main solar and wind technologies will be compared against the conventional energy systems of Northern and South Cyprus based on their Levelized Cost of Energy (LCOE) of their sold or to be sold electrical energy.

The software tool called System Advisor Model (SAM) has been used in this study. SAM is a performance and financial model designed to facilitate decision-making for people involved in the renewable energy industry.

For this particular study, a weather file in EnergyPlus Weather (EPW) file format was used. This data file is downloaded from the international weather databases of the U.S Department of Energy. The weather file consists of data sets which have been constructed from the years 1985 to 1995. The details of this dataset were presented as solar and wind data in chapter 2.

Sensitivity studies were conducted to define an optimal value for both loan term and PPA escalation rate in order to minimize the LCOE. This sensitivity study studied a PPA escalation rate from 1 to 3 per cent in 0.5 per cent steps and loan term from 10 to 30 years in 5 year steps. The results of the sensitivity study for defining loan term against escalation rate indicated that the choice of loan term of 30 years with a PPA escalation rate of 1.5 per cent would have the lowest LCOE. Hence these values are chosen for use in this study.

In order to enable CSP technologies to store and dispatch energy when the sun is shining, means of storage are required. The size of storage and the power block as well as the size of the solar field determines the amount of dispatch capacity (in hours).

Using the SAM software, these parameters are tested for the CSP tower plant and CSP trough plant. The system is tested with solar multiples from 1 to 3 in 0.5 steps against solar storage hours for each of 24 hours against plant capacity output from 50MW to 250MW with 10MW increments. Therefore for each CSP technology, in order to determine the lowest LCOE with these 3 variables, a total of 3150 simulations were run.

According to the simulation results, regarding the lowest LCOE when checked against the CSP tower output capacity, it is lowest at 130MW. However, there is a logarithmic decline in LCOE when the output capacity increases from 50MW up until 120MW. From 120MW to 190MW, there is almost a plateau of the level of the LCOE. From 190MW and up, again it is observed that there is a steep rise in the value of the LCOE. Therefore, the optimum output level at 130MW generates the minimum LCOE for CSP tower. On the other hand, for CSP trough systems, LCOE value is unaffected by the output capacity of the plant.

It is observed that there is a parabolic nature of LCOE when increasing the thermal storage hours. On each parabola of the different value of the solar multiple, it can also be observed that there is the minimum LCOE. Among these minimums solar multiple at 2 and thermal storage hours at 4 hours generated the lowest LCOE. However, the LCOE values at the minima points are within 2 per cent of the lowest LCOE except for solar multiple of 1.5 which is 14 per cent away from the lowest LCOE.

The results following the simulations of solar multiple against the thermal storage hours of the CSP trough plant indicated that there is a linear increase of LCOE when solar thermal storage hours are increasing for solar multiples of 1 and 1.5. On the other hand, there is a parabolic nature of LCOE with the increasing the thermal storage hours for solar multiples of 2 and above. Among the results, solar multiple at 1.5 and thermal storage hours at 1 hour generated the lowest LCOE.

In order to be able to demonstrate the results against the current electricity system, the trend of electricity price of the KIBTEK from 1995 until today has been extrapolated throughout the years 2013 to 2042. Three scenarios are illustrated, called “Scenario – Parabolic”, representing the most probable and highest rise in cost of electricity, “Scenario – Linear Medium” and “Scenario – Linear Low” representing a slower rise in the cost of electricity.

Using these three scenarios, four different cases for each RES technology are compared to each other and to the cost of electricity of conventional generation. The four cases are 2013 with DSCR 1.1, 2013 with DSCR 1.5, 2020 with DSCR 1.1, and 2020 with DSCR 1.5. The cases concerning year 2013 represent the projects with present-time costs. The cases concerning 2020 are based on the future costs estimated by this study by surveying published sources. The DSCR is the ratio of operating income to costs in a given year. Hence, present and future projects with different DSCR ratios are studied against three different trends of present and future cost of electricity from conventional generators.

With the case of 2013 with DSCR 1.5, the results were as follows: On the basis of LCOE, Wind power has the lowest cost of approx. 25 cents/kWh compared to CSP tower at 30 cents/kWh, CSP trough plant's at 34 cents/kWh and 43 cents/kWh of PV plant. This significant difference of cost is reflected to the cost of electricity and to the years taken to at least match the cost of electricity of conventional power plant electricity of KIBTEK. In this sense, Wind power takes almost 25 years to match KIBTEK's cost of electricity. On the other hand solar technologies fail to reach a price as low as the KIBTEK's cost of electricity within their operational lifetime of 30 years.

With the case of 2020 with DSCR 1.5, the result were as follows: On the basis of LCOE, Wind power has the lowest cost of approx. 14.7 cents/kWh compared to CSP tower at 23.3 cents/kWh, CSP trough plant's at 33.96 cents/kWh and 27.46 cents/kWh of PV plant.

In year 2020, Wind power is almost as low as the "scenario low" of cost of electricity from conventional generators. It is almost \$0.05/kWh lower than the "scenario – parabolic". On this occasion, CSP tower manages to match the cost of electricity of conventional generators after 8 years and remaining solar technologies after 17 years of operation.

With the case of 2013 with DSCR 1.1, the results were as follows: On the basis of LCOE, Wind power has the lowest cost of approx. 20.6 cents/kWh compared to CSP tower at 24.31 cents/kWh, CSP trough plant's at 27.6 cents/kWh and 33.8 cents/kWh of PV plant.

It has been shown that it will take 14 years for Wind technology to match the cost of electricity from conventional generators. CSP tower manages to match the cost of electricity of conventional generators after 23 years. On the other hand remaining solar technologies fail to reach a price as low as the KIBTEK's cost of electricity within their operational lifetime of 30 years.

With the case of 2020 with DSCR 1.1, the results were as follows: On the basis of LCOE, Wind power has the lowest cost of approx. 10.95 cents/kWh compared to CSP tower at 18.68 cents/kWh, CSP trough plant's at 22.28 cents/kWh and 21.99 cents/kWh of PV plant.

It has been shown that it will take approx. 5.5 years for PV and CSP Trough technologies to match the cost of electricity from conventional generators. Wind technology on the other hand is almost \$0.05/kWh lower than the scenario-low costs of KIBTEK whereas CSP-tower is lower than “scenario-parabolic” and almost identical to the “scenario-medium” of estimated conventional generators’ cost of electricity.

Among these technologies, Wind has the minimum land area usage and the lowest LCOE followed by the CSP tower in terms of the LCOE and energy price. Installation cost of CSP trough and PV plants differs by almost 20 per cent. However, the land area usage differs by approximately 100 per cent. In that sense, PV plant occupies half of the land area used by the CSP trough plant. On the other hand CSP tower plant requires nearly 10 times more land than the PV plant. The amount of land is a function of the solar multiple and CSP tower has a solar multiple of 2 in order to be able to utilize large storage capacity hence the very high requirement for land area.

In terms of estimated annual GHG emissions reduction per installed capacity, which is directly related to the capacity factor of the RES technology, CSP tower has the highest reduction in emissions as much as 1919 tonnes per installed MW per year with the highest load factor of 28.1per cent whereas wind power has the lowest capacity factor of 17.0 per cent with lowest GHG emission reduction of 1163 tonnes per installed MW per year.

In order to be able to demonstrate the effect on the demand curve by using RES technologies along with conventional generators, the daily electricity curve with and without the RES contribution has to be illustrated. For demonstration purposes three typical days of the year from January, July and November are chosen.

It was observed that wind energy is offsetting the conventional generation throughout the day. The amount of offset depends on the time, day and the season of the year. PV on the other hand starts offsetting conventional generation from sunrise to sunset. The overall impact is that the plateau demand from morning to late afternoon is reduced and troughed. The evening peak remains the same. Compared to PV, CSP plants are starting to produce electricity after a couple of hours delay due to the requirements of steam boilers and storage facilities. CSP trough has rather a short storage capacity and hence is demonstrating similar behaviour to the PV. However, CSP tower, due to its size and long storage capacity, is able to offset large amounts of conventional generation, starting from morning until late night time and its output can be varied according to the operators' needs.

Two different cases of CSP tower are calculated. The case called "Tower" is demonstrating a case in which storage capacity is actively used to store and dispatch energy, maximizing the instantaneous output when the sun is shining. On the other hand the case called "Tower2" illustrates one of the biggest advantages of CSP storage which is the use of storage to offset the conventional generation by following the demand curve and offsetting the conventional generation to a fixed level.

The resultant fixed level of conventional generation means that conventional generation can run as base load units and solar CSP will vary its output with use of its storage capabilities by following the demand curve. Therefore by fully utilizing storage capabilities, the daily peak demand no longer exists and it is reduced from 200MW to 107MW. On the other hand, the daily peak demand is reduced from 152MW to 51MW in November and 192MW to 52MW in January. An immediate advantage of this load profile smoothing is that the operators can make best use of the base load generation, namely fuel oil, and avoid using the faster response diesel generation.

7.2. Main contributions

1. The electricity demand in Cyprus is increasing. This increase compared with the electricity demand in 2010 will range from 33 to 46 per cent for Northern Cyprus and 36 to 53 per cent for the South Cyprus until 2020.
2. Cyprus should adapt established renewable energy policies from developed European countries in order to increase the amount of implementation of RES technologies in the island. The current Cypriot electricity generating system is averaging an overall efficiency of power generation since 2006 of 36 per cent. The published data of the European Environment Agency (EEA) regarding the CO₂ generated electricity per kilowatt hour in 2009 per member country indicated that Cyprus is one of the highest emissions producers with a 0.67 kg per kWh.
3. Wind energy is the cheapest option for the years to come. Although, the mean annual wind speed (m/s) of the island have a mean wind speed range of 3 to 4 m/s and areas near the coast have a mean speed range of 4 to 5 m/s, due to maturity of the wind technology and it's established industry, the upfront costs are less than the solar technologies.
4. High temperature storage enables solar technologies to have high load factors and makes them dispatchable. Although, solar energy is more expensive than the wind energy, high load factor lowers the levelized energy cost compared to those solar technologies without energy storage. Also, energy storage enables system operators to dispatch energy on demand.

7.3. Topics for future research:

In determining the exact theoretical upper limit of the level of penetration for grid connected RES generation; a power system model can be prepared with all the transmission system, generation system and distribution system built in for Cyprus. Using this model, then connection of RES generation at the test locations can be simulated and tested.

Studies, using the power system model, can be simulated to assess the impact of wind power on the operation of island's power systems. The analysis can focus on the availability and flexibility of the thermal generation to balance wind variations and wind forecast errors. With large amounts of wind penetration, the effects of wind power curtailment and/or demand shedding can be studied. Revision of reserve requirements and its economic impact can be studied.

This research has concentrated on the use of large scale RES technologies connected to a high voltage transmission system. Another important prospect for research can be the generation connected to the distribution system, or even at consumer-level distributed generation. These forms of generation would not necessarily appear on the system or grid operator's system, but the resultant effect would be reduced demand or change of demand curve or demand profile behaving differently than forecast. This would in effect result in the system operator extending the conventional methods of system operation, hence will require further research.

This research promotes the grid code changes in order to enable grid operators to connect and manage utility-scale RES solutions. Following the amendments to the grid code, energy and renewable energy policies are most likely to be introduced in order to enable industries or investors access to the grid system to make investments in RES technologies. These policies on the other hand may enable large utility-scale solutions as well as small domestic solutions. The current system has been designed in such a way that energy is always flowing from generator to demand. Since there are only a small number of generators and clusters of demand, with the introduction of these policies, and hence introduction of domestic scale RES solutions as well as large scale solutions, the pattern of energy flow may change. System losses, islanding issues, voltage fluctuations, protection systems and simple infrastructure changes may be required. There is a good opportunity for research to look into the effects of policy-making and the resultant connection of more large, as well as domestic, RES solutions.

CHAPTER 8

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CHAPTER 9

PUBLICATIONS



List of publications of the author

9. List of publications

Authors:

Davut Solyalı ⁽¹⁾, Dr. Miles A. Redfern ⁽²⁾

(1) University of Bath, Student member of IEEE

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Conference Paper1:

UPEC 2009

The 44th International Universities' Power Engineering Conference

1-4 September 2009

Title: HAVE WIND TURBINES STOPPED MATURING?

Conference Paper2:

EPE 2010 (ELECTRIC POWER ENGINEERING)

The 11th International Scientific Conference

4-6 May 2010

Title: CASE STUDY OF CYPRUS: WIND ENERGY OR SOLAR POWER?

Conference Paper3:

ICCE 2010

The 10th International Conference on Clean Energy

15-17 September 2010

Title: EXPLOITING SUNS'S ENERGY – COMPARISON OF SOLAR TECHNOLOGIES FOR CYPRUS

Conference Paper4:

UPEC 2011

The 46th International Universities' Power Engineering Conference

5–8 September 2011

Title: WHY SHOULD CYPRUS EXPLOIT THE SOLAR POWER TO MATCH ITS
PEAK DEMAND?

Conference Paper5:

EPE 2012 (ELECTRIC POWER ENGINEERING)

The 13th International Scientific Conference

May 2012

Title: USING PV SYSTEMS TO IMPROVE ENERGY SAVING: - CASE STUDY OF
CYPRUS

Journal Paper: (Pending)

IEEE – Sustainable Energy Journal

Title: COMPARISON OF LARGE SCALE RES GENERATION IN NORTHERN
CYPRUS – AN ECONOMIC AND OPERATIONAL REVIEW